THE EFFECTS OF COMPRESSION ROLLING ON SAWN TIMBER

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To my family

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ABSTRACT

The effects of a mechanical process termed "Compression rolling" on the structure of sawn timber have been investigated in the course of this work.

1. A wood rolling mill was designed on the basis of preliminary experiments and the experiences of previous workers. The multi-functional rolling device contains a series of innovations which were necessary to test the effects of different rolling parameters on the timber structure.
2. A multifactorial, randomized, fully- replicated block design was set up to determine the effects of the process on the diffusivity and on the permeability of <u>Nothofagus fusca</u> heartwood (New Zealand red beech). The results showed that the process had a pronounced effect on permeability, which was assessed after a pressure treatment with CCA preservatives, whereas the drying characteristics were only modified to a minor degree.
3. The importance of level of saturation at the time of rolling was determined. With a decrease in moisture content structural alterations were increasingly confined to microscopic damage, whereas application of the process to highly saturated boards resulted in substantial macroscopic damage. Thus any advantage in compression rolling with respect to drying is vitiated by having to pre-dry before hand!
4. Detailed scanning electron microscopical (SEM)

examination was undertaken to observe anatomical alterations induced by compression rolling of red beech. Most noticeable was the effect on the vessels and on the intra- and intervascular structure (perforation plates, tyloses and vessel to vessel pits), which appeared deformed and occasionally collapsed and ruptured.

5. The SEM was used to investigate the effects of hot water soaking and compression rolling. The recorded improvements in drying rate were attributed to the dilution and partial extraction of phenolics from the ray parenchyma and its redistribution, whereas the subsequent rolling process was not able to increase further the radial or tangential drying rate.
6. The effects of rolling on the structure and permeability of the heartwood of two refractory softwoods (Pseudotsuga menziesii and Picea sitchensis) were determined. In both species permeability was only improved to a small extent and the improvement observed was confined to small bands mainly within the latewood.
7. Similar structural alterations in both species at macroscopical and microscopical level are indicative of an irregular strain distribution throughout the boards. This was attributed to a large variation in density and inherent permeability between earlywood and latewood.

AUSWIRKUNGEN EINES ROLL-DRUCKVERFAHRENS AUF SCHNITTHOLZ

ERWEITERTE ZUSAMMENFASSUNG

Die Auswirkungen eines mechanischen Rolldruck-Verfahrens ("Compression rolling") auf die Holzstruktur von Schnittholz (Nothofagus fusca, Picea sitchensis und Pseudotsuga menziesii aus neuseelaendischen Wuchsgebieten) wurden in der vorliegenden Arbeit untersucht. Widerspruechliche Ergebnisse und unzureichende Informationen in der Literatur, die das urspruengliche in Kanada entwickelte Verfahren (Goulet, 1968) testen oder besprechen, waren der Anlass fuer die vorliegende Studie. Das Entwicklungs- und das gegenwaertige Stadium der Versuche kann wie folgt zusammengefasst werden:

1. Auf der Basis von bisherigen Erfahrungen mit der Konstruktion von Holz-Roll-Druckanlagen und eigenen im Labor durchgefuehrten Testreihen zur Ermittlung konstruktionstechnischer Faktoren, wurde eine Rollanlage entwickelt und konstruiert. Die vielseitige Anlage enthaelt eine Anzahl von Veraenderungen im Vergleich mit den bisherigen Maschinen, die jedoch notwendig waren, um den Einfluss verschiedener Roll-Faktoren auf die auf die Holzstruktur zu testen. Es war jedoch nicht moeglich, das Verhalten der Maschine zu optimieren und gegenwaertig werden die notwendigen Aenderungen zur Leistungsverbesserung und der Neuentwicklung des Messkreises erarbeitet.

2. Die Einfluesse des Verfahrens auf die Permeabilitaet und auf das Trocknungsverhalten von Nothofagus fusca (Kernholz) wurden mit einer Multi-Faktor Varianz Analyse getestet. Die Ergebnisse zeigten, dass "Compression Rolling" die Permeabilitaet entscheidend verbessert, waehrend die Trocknungszeit von waldfrischem, "gerollten" Schnittholz nicht entscheidend verkuerzt werden kann.

3. Eine 20-stuendige Heiss-wasserbehandlung in Verbindung mit dem Roll-Verfahren beeinflusste die Permeabilitaet und das Trocknungsverhalten entscheidend. Die Traenkung allein verkuerzte die Trocknungszeit von N.fusca Schnittholz um fast 50%, waehrend Permeabilitaet nur minimal verbessert wurde. Letztere konnte nur nach zusaetzlichem "Rollen" erhoeht werden, hingegen beeinflusste diese zusaetzliche Behandlung die Trocknungszeit nicht und verzoegerte diese leicht.

4. Der Einfluss des Holzfeuchtigkeitsgehaltes waehrend des Rollvorganges wurde bestimmt. Mit Abnahme der Holzfeuchte konnten die strukturellen Veraenderungen auf den mikroskopischen Bereich konzentriert werden, waehrend "Rollen" von waldfrischem, beinahe wassersattem Material deutlichen makrostrukturellen Schaden verursachte. Falls Druck-Rollen tatsaechlich, wie urspruenglich patentiert, das Trocknungsverhalten von impermeablen Holzarten verbessern sollte, so ist es zumindest nicht empfehlenswert fuer Holzarten von hohem urspruenglichem Feuchtigkeitsgehalt.

5. Ausfuehrliche Raster - Elektronen - Mikroskopische (REM) Untersuchungen wurden unternommen, um die verfahrensbedingten Veraenderungen in der Holzstruktur festzustellen. Deutlich wurde hierbei, dass hauptsaechlich das vaskulaere Gewebe (Gefaesse und Gefaessinhalte, z.Bs. Thyllen und skalariforme Gefaessunterbrechungen) in unterschiedlichem Mass beschaedigt wird. Die angrenzenden Fasern und das Holzstrahl- parenchym sind weniger betroffen. Die substantielle Verbesserung der Druck-Impraegnierbarkeit von N.fusca ist hauptsaechlich auf die resultierende erhoehte axiale und tangentiale Permeabilitaet zurueckzufuehren.

6. REM-Beobachtungen von Praeparaten heiss-wasserbehandelter und zusaetzlich "gerollter" Bretter wurden unternommen. Ursaechlich fuer das verbesserte Trocknungsverhalten nach dem ersteren Verfahren waren hauptsaechlich strukturelle Veraenderungen der Inhaltsstoffe im Holzstrahl-Parenchym, die zum Teil aus dem Holz ausgelaugt wurden. Das Rollverfahren bewirkte lediglich eine unregelmaeissge Beschaedigung der radialen Holz-strahlwaende und verursachte nicht (wie erhofft) eine gezielte Tuepfelmembranbeschaedigung.

7. Die Auswirkungen des Roll-Druckverfahrens auf die Anatomie und die Permeabilitaet des Kernholzes von zwei beschraenkt permeablen Nadelhoelzern (Picea sitchensis und Pseudotsuga menziesii) wurden untersucht. In beiden Holzarten konnte eine maessige Verbesserung der

Traenkbarkeit festgestellt werden, jedoch war die Holzschutzmittelverteilung ueber den Brettquerschnitt aeusserst unregelmaessig und hauptsaechlich auf schmale Spaetholzzonen konzentriert.

8. Die Gruende fuer die unzureichende Verbesserung der Traenkbarkeit wurden mit optischen und mikroskopischen Mitteln untersucht. Makro- und mikrostrukturelle Veraenderungen zeigten deutlich, dass der Rolldruck unregelmaessige Verdichtungen ueber den Querschnitt des Brettes verursacht. Dieses ist bedingt durch Zonen unterschiedlicher Dichte (eine ausgepraegte Holzeigenschaft der beiden getesteten Holzarten). Zusaetzlich zeigt das weniger dichte Fruehholz eine groessere Verformbarkeit im elastischen Bereich, was zum Teil auf das guenstigere Verhaeltniss Zell-lumen:Zellmatrix, aber auch auf die geringere Permeabilitaet zurueckzufuehren ist. Das Verhalten von Holz bei Verdichtungen in den getesteten Groessenordnungen (10% bis 20%) wurde mit dem eines geschlossen-zelligen Schwammes verglichen; eine separate Studie koennte ermitteln, ob der beobachtete Zusammenhang zwischen Dichte, Permeabilitaet und elastischer Verformbarkeit allgemein Gueltigkeit haben koennte. Die vorliegende Arbeit bestaetigte die urspruengliche Vermutung nicht, dass Tuepfelmembranen durch den Rollvorgang gezielt zerstoert werden koennen.

CHAPTER 1: INTRODUCTION

1.1. REFRACTORY SPECIES AND THE NEED FOR PROCESSES TO INCREASE THEIR DIFFUSIVITY AND PERMEABILITY

Two of the most important steps in the conversion of logs into various timber products are appropriate seasoning and adequate protection of the timber against deterioration. There are great differences between the 10 000 or so known timbers of economic relevance as far as their response to the different stages of processing is concerned. While physical properties of timber such as specific density, modulus of elasticity, modulus of rupture, shear and torsional strength represent important parameters to be considered when wood is selected for its final use, anatomical characteristics are of principal significance during the early stages of processing - the drying or seasoning of the material to equilibrium moisture content (EMC) and the subsequent treatment with chemicals to preserve against environmental hazards.

Species are divided into three main groups according to the ease with which the sap present in the wood can be removed during drying without degrade, and also according to the extent to which fluids can penetrate the timber in subsequent treatment processes: The first category includes all timbers which do not offer significant resistance to fluid movement; these are listed as "permeable species"; the second group is described as "semipermeable species", where increased resistance arising from to the anatomical structure causes problems during the drying and/or treatment process; the third group comprises "impermeable species", which can only be dried very slowly or using special techniques and of which the majority are considered "untreatable". Technical difficulties in achieving adequate drying and preservative penetration have for a long time limited the utilisation of timber species in the third category.

Numerous efforts have been undertaken to overcome impermeability, including solvent seasoning (Ellwood and Ecklund, 1963) and other chemical infusions to decrease sap-surface tension (Lantican, Cote and Skaar, 1965), steaming (Kubinsky, 1971; Haslett and Kininmonth, 1975), biological pretreatments (Bauch, Liese and Berndt, 1970) and also simple mechanical techniques such as roller destructuring (Puri and Higgins, 1982), incising (Banks, 1973; Perrin, 1978) and compression rolling (Goulet and Cech, 1967). Although the majority of these processes have a positive effect either on the drying behaviour or on the treatability, most of them are too expensive to apply or simply commercially impracticable. Compression rolling is one mechanical process, which has been the subject of a series of investigations over the last 15 years, although it has not yet been used commercially. Results and conclusions drawn from these experiments vary to such an extent that a further in depth study of the process appeared not only justifiable but necessary.

1.2. EXPLANATION OF GOULET'S COMPRESSION ROLLING WORK AND REASONS FOR COMMENCING STUDIES AT THE UNIVERSITY OF CANTERBURY

This mechanical approach to overcome the resistance of impermeable (or refractory) timbers to moisture movement, either during drying or during preservative treatments, was developed in Canada (Goulet, 1968). The process, known as dynamic transverse compression rolling or compression rolling, had significant influence on the drying characteristics and permeability of species,which had been subjected to the rolling process. The technique involves feeding sawn boards through a pair of contrarotating rollers and thus subjecting the timber to a transverse compression; the rate and level of compression depends on the roller diameter, and the gap between the rollers and the feed speed. Hallett (1984, personal communication) indicated, that the original idea of compression rolling dates back to 1940, when unpublished experiments were conducted in Denmark. Subsequent enquiries with regards to specific information regarding this work could not substantiate this comment.

Goulet (1968) postulated that during the compression cycle damage is induced in the tissue at the microscopic level which has a positive influence on the subsequent drying characteristics and/or on the treatability of the timber. It was argued that a combination of hydraulically and mechanically induced stresses ruptured pit membranes without causing substantial damage to the cell-wall itself, thus opening the timber for fluid flow, without a significant concommitant loss in mechanical strength (Goulet, Cech and Huffman, 1968; Cech and Huffman, 1970; Cech, 1971).

The exact mechanisms involved in compression rolling are not fully understood. Bearing in mind the viscoelastic nature of wood and the involvement of fluid flow, a strong relationship between the rate of compression and the damage can be expected. This and other factors which might play a significant role in the efficiency of the rolling process and its potential application were not sufficiently appreciated in previously published work.

1.3. AIMS OF INVESTIGATION

All experiments to date were proposed to test the effects of the technique on one of two properties, diffusivity and permeability separately. Indeed no species was compression rolled and subsequently tested for both improvements in its drying characteristics and in its preservative uptake. This divorce between drying and preservative treatment studies was also noted in the selection of timber: softwoods were only tested for permeability while hardwoods were exclusively tested for their diffusivity (see Tables 2.3 and 2.4). According to Stamm (1967),"..Both liquids and vapours can move through the coarse capillary structure under two different laws, namely by pressure permeability and by diffusion..". It seems to have been tacitly assumed that eventual structural alterations to the wood resulting from a mechanical process, might have similar effects on both properties, "..Variations in structure can thus affect the type of movement as well as the rate.." (Stamm, 1967).

The present study was therefore set up partially to repeat the original work described in the patent (Goulet, 1968), but also to establish the effects of the treatment on both mechanisms of moisture movement (diffusion and permeability) on the same species. A timber was sought for the experiments which was considered difficult to dry and completely impermeable to pressure treatments by preservatives. The heartwood of Nothofagus fusca fulfils these requirements showing high resistance to the movement of fluids through its tissues, irrespective of the driving force (moisture , vapor pressure or pressure gradient).

A joint research project was therefore initiated at the University of Canterbury between the Department of Mechanical Engineering and the School of Forestry in order to gain a broader understanding of the process. The objects were to:

1.3.1. Design

Design an experimental compression rolling machine with high level of accuracy and reliability to provide interpretable results

1.3.2. Experimental

Gain an understanding of the mechanism involved in compression rolling timber and the relationship between such parameters as:

(1) Compressive strain

(2) Linear speed

(3) Roller Diameter

(4) Timber characteristics (species, density, moisture content, grain orientation etc) and the response of the wood structure to the rolling process.

1.3.3. Analysis

Establish the effectiveness of the compression rolling process in improving the drying rate and the preservative uptake characteristics of New Zealand grown species.

1.3.4. Optimisation of the method

Eventually determine the optimum operating parameters for the design of a commercially viable process.

1.4. POTENTIAL OF COMPRESSION ROLLING FOR TIMBER UTILISATION IN NEW ZEALAND

Although New Zealand relies on an exotic pine (*Pinus radiata*) for 90 percent of its timber production - and this timber is highly permeable - a proportion of its remaining indigenous forest contains potentially valuable timber resources especially for decorative uses. Some of these timbers are considered to be completely impermeable and of high inherent durability. Species, especially within the family of the *Nothofagaceae*, could significantly increase their utility and value if the problems in seasoning were to be overcome. *Nothofagus fusca*, New Zealand Red Beech, a species growing mainly in untended forests of the West Coast of the South Island, has excellent timber characteristics once it has been dried down to EMC around 10 % moisture content (Parham, 1933; Kininmonth, 1965; Forest Research Institute, 1974). Nevertheless the extremely long air-drying period (12 month for each 25 mm board thickness) represents a severe limitation to its economical utilisation. At present the Red Beech resource is not being fully or effectively utilized. Red beech was therefore selected for these compression rolling studies. Several alternative exotic species grown in New Zealand have the same problems of low diffusivity and permeability and could be subjects for future compression rolling experiments.

Amongst the hardwoods, eucalypts represent the most obvious candidate, due to their well known difficulty in drying and seasoning. Amongst the softwoods, Douglas fir and species of the genus *Picea* are categorized as impermeable timbers. Although their seasoning does not cause comparable difficulties to those experienced with most impermeable hardwoods, preservative treatments generally produce unsatisfactory results.

CHAPTER 2: LITERATURE REVIEW

2.1. PERMEABILITY

Permeability, as defined by Siau (1971), "...is a measure of the ease with which fluid flows through a porous material under the influence of a pressure gradient...". Where this refers to steady-state flow of fluids through wood, assuming constant flow per unit cross-section (= flux) under a constant pressure gradient, the behaviour is described in Darcy's law:

$k =$ flux/Gradient $= (V \times L)/(t \times A \times \Delta P)$; (Equation 2.1.),

where

k = Permeability $(mm^4$ (liquid)) / $(N \times s)$
V = Volume of liquid flowing through specimen (mm^3)
t = Time of flow (s)
L = Length of specimen in direction of flow (mm)
A = Cross-sectional area of specimen perpendicular to the direction of flow (mm^2)
ΔP= Potential, pressure gradient (N / mm^2)

For gaseous flow a change in the volume flow due to the expansion of gas can be included into Darcy's law, which is then written as:

$k_g = (V \times L \times P) / (t \times A \times \Delta P \times \bar{P})$, (Equation 2.2.)

where
P = Pressure at which V is determined (N/mm^2)

$\bar{P}$ = Average pressure along the length of the specimen (N/mm^2)

Pressure permeability is an important parameter when timber is subjected to preservative treatments with alternative vacuum/pressure cycles, and where total uptake of preservative solution depends on the accessible pathways for preservative penetration. Several methods have been developed to measure permeability, such as the Rising-Water Volume-Displacement method, Falling-Water Displacement method, the Rotameter method (Siau, 1971) and Permeability Cells (Choong and Kimbler,1971; Booker, 1980).

Variation in permeability between species and within species of different origin is substantial, as illustrated schematically in Table 2.1 : (The heartwood of Nothofagus fusca is grouped amongst the most impermeable medium density species of commercial interest; neither transverse nor axial permeability is measurable (Kininmonth, 1971).

$$\frac{(mm^3\ (air))}{mm \times kPa \times s}$$

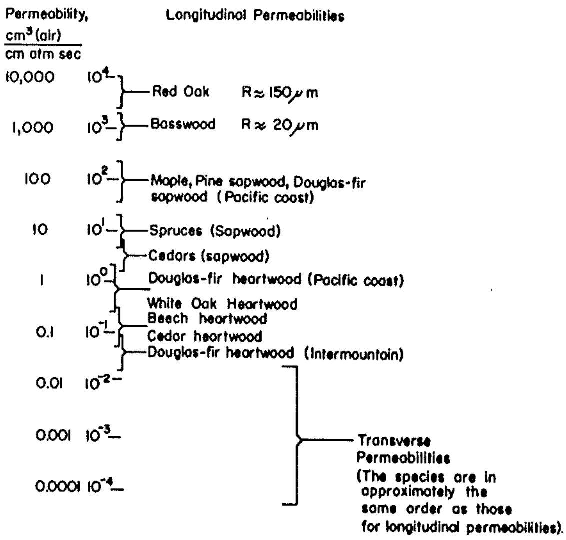


Table 2.1 List of some softwoods and hardwoods to illustrate the ranges of permeability (Siau, 1971)

2.2. DIFFUSIVITY

Analogous to the definition of permeability, diffusivity will be defined here as the measure of ease with which a fluid moves through a porous (low permeable) material under the influence of a moisture gradient. In wood moisture diffusivity comprises two principal diffusion factors, water vapor diffusion and bound water diffusion. Diffusional processes normally dominate the later stages of drying wood below fibre saturation, when cell luminae no longer contain sap, and the remaining moisture is present either as vapor or as bound water in the cell walls. Water vapor diffusion (Dv) is substantially greater than bound water diffusion (Db), and the relationship between Dv and Db can vary from 10 : 1 at moisture content close to fibre saturation point to 1000 : 1 when close to the oven dry state. The overall characteristics of diffusivity for a timber species are strongly influenced by wood anatomical features, such as density, presence of extractives, grain orientation, etc.

In the early stages of drying of permeable timbers in which the cells are partly or completely saturated with sap, diffusional movement is considered negligible in comparison to mass flow induced by capillary and pressure gradients. The resistance of wood to pressure induced sap flow, characterized by the wood's permeability, determines the extent to which "free" circulation can occur. In species with very low permeability (Table 2.1) mass flow is restricted in all stages of drying, hence all moisture present in the wood can only be removed by diffusion.

Water vapor diffusion is governed by Fick's first law, which defines the conductivity coefficient as a function of flux and moisture gradient:

$$k_d = (m \times L) / (t \times A \times \Delta MC), \qquad \text{(Equation 2.3.)}$$

where

k_d = Conductivity coefficient for water vapor diffusion through wood (kg / (mm x %x s)

m = Mass of water vapor transported through the specimen in kg

L = Length of specimen in flow direction in mm

t = time for flow (s)

A = Cross-section area of specimen perpendicular to the flow direction in mm^2

MC = Moisture content in %

ΔMC = Moisture content difference between two parallel conducting surfaces separated by a distance L, (expressed as kg moisture content/kg dry wood)

Moisture content difference can also be expressed as difference in moisture concentration, which is applied for the definition of the water vapor diffusion coefficient:

$$D_g = (m \times L) / (t \times A \times \Delta MC \times G \times \rho w), \qquad \text{(Equation 2.4.)}$$

where

D_g = Water vapor diffusion coefficient of gross wood (mm^2/s)

G = Specific gravity of wood at moisture content MC

(ρw = Normal density of water (kg/m^3)

Bound water diffusion on the other hand is a more complex phenomenon, which cannot be summarized in a comparable equation. One has to distinguish between the transverse and longitudinal bound water diffusion coefficient, the latter being roughly 2.5 greater than the former (Siau, 1971). It is further influenced by moisture content and temperature which in the course of the drying process do not remain constant.

Drying of permeable timber below fibre saturation and drying of impermeable timber from high saturation are hence a function of the two diffusion components bound water (Db) and water vapor (Dv). Drying in the transverse direction (assuming similar tangential and radial diffusion coefficients) is restricted by crosswalls, hence total transverse diffusivity is primarily influenced by the bound water diffusion coefficient, whereas by comparison Dv can be neglected (Siau, 1971):

$$D_{gT} = D_{bT} \; / \; (1-a^2) \times (1-a), \qquad \text{(Equation 2.6.)}$$

where

D_{gT} = Transverse water-vapor diffusion coefficient of gross wood in m/s

D_{bT} = Transverse bound-water diffusion coefficient in m/s

a = Model parameter = $\sqrt{V}$, V = Porosity of wood

In the longitudinal direction there is less restriction to axial water vapor diffusion, due to the low frequency of crosswalls and more pronounced pitting of these tracheid crosswalls in the case of softwoods and due to the presence of open vessel connections in hardwoods. Thus the longitudinal diffusion in the equation becomes:

$$D_{gL} = ((V_a \times D_v)) / (1-V_a)) + D_{Bl} \qquad \text{(Equation 2.7.)}$$

D_{gL} = Longitudinal water-vapor diffusion coefficient of gross wood in m/s

The three different paths for diffusion in wood are illustrated in Figure 2.1 , as suggested by Stamm, (1967):

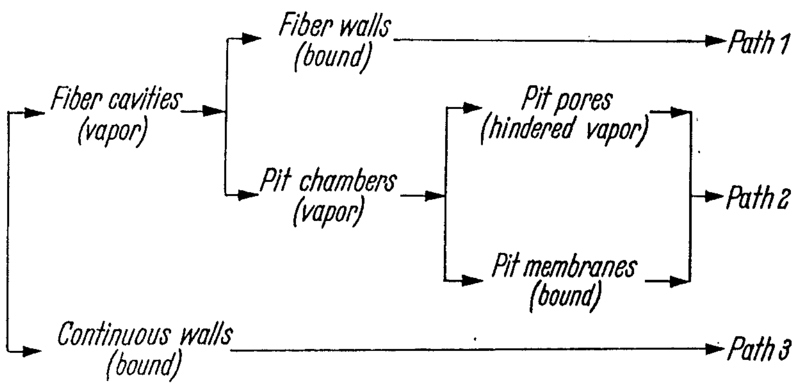


Figure 2.1. Diffusion pathways through wood (according to Stamm (1967)

2.3. EFFECTS OF COMPRESSION ROLLING ON THE DRYING OF TIMBER

2.3.1. Summary of the literature

The original published work on compression rolling dates back to 1967, when a Canadian scientist, Marcel Goulet, applied for a patent under the title: " A method of drying solid timber " (Goulet, 1968). The process is described as being applied to green, highly saturated boards of Yellow birch (Betula alleghanensis) immmediately after sawing. The timber was subjected to a short-term compressive stress of around 8 N / mm^2, while being fed through a pair of compression rollers. The results appeared extremely promising:

"..L'économie de temps attribuable au procédé qui fait l'objet du présent brevet est donc de plus de soixante pour cent, ce qui est considérable.." (Goulet, 1968). He claimed subsequent savings in the order of 60 percent when drying the rolled timber. Although the patent does not contain any extensive explanation about the mechanisms causing this acceleration in drying, the inventor recommends his technique for other timbers of low permeability such as oaks and European beeches. These findings are underlined in the first publications by Goulet and Cech in 1967, where "..a reduction in duration of drying in the proportion 1:6 .." was recorded, again with Yellow birch. Furthermore they indicated that the rolled material dries better, in that the boards are of better quality compared to the untreated controls.

A comprehensive study by Cech in 1971 to "..determine the optimum compression level for improving the drying behaviour of 2-inch Yellow birch lumber and to explain the basic reasons for the improvements.." described the rolling equipment followed by an extensive description of drying behaviour, and included information about "moisture conductivity" variations,the effect of the process on the strength properties and, finally some anatomical studies to elucidate why the timber dried faster. For example Cech claimed that while a 12.5 per cent compression of green timber only reduced the required drying time during a high-temperature kiln schedule insignificantly from 200 hours for controls to 192 hours, it produced timber free of substantial collapse and internal checking, which was present in controls. Alternatively, a similar end-quality for timber not subjected to transverse compression could only be obtained with conventional kiln schedules which extended the drying period to 430 hours. Subsequent tests (Cech 1971) to determine moisture conductivity coefficients of compression rolled boards in comparison to controls revealed that an optimum compression level of 8.5 percent "... gives larger increases for impermeable material, but the effect decreases very sharply to no increase for specimens with a basic (inherent) rate of moisture evaporation about 0.05 g/hr..." (against 0.02 g/hr in the more impermeable material; Figure 2.2). The implication is that compression rolling only enhances the rate of drying for more impermeable woods.

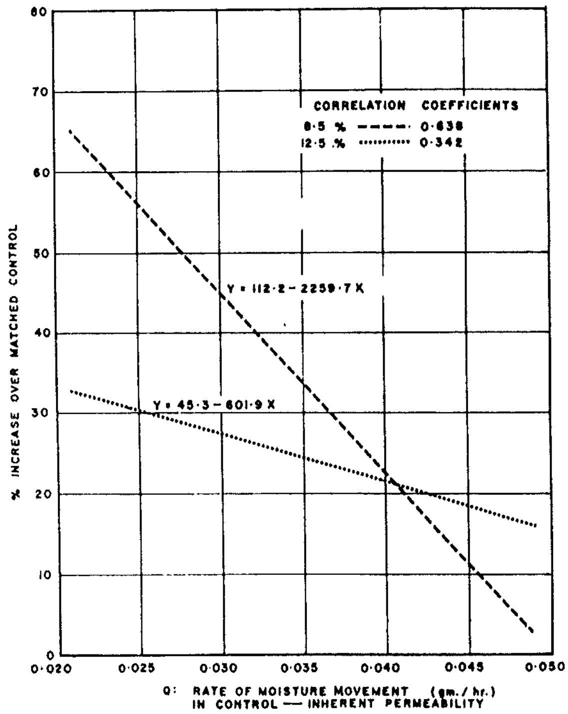


Figure 2.2 Influence of " inherent wood permeability " on the percent increase in moisture movement rate resulting from transverse compression treatment (Cech, 1971)

The strength properties of yellow birch were not reduced noticeably when the compression level was around 8.5%, percent, whereas the modulus of elasticity was reduced by 10% and the maximum bending strength by 4%, when a 12.5% compression was applied. It is suggested that an optimum compression level should be established for each species individually. Anatomical examination of rolled specimens revealed numerous splits in vessel-pit-membranes, which "...provide an explanation for the improved moisture conductivity of treated wood..." (Figure 2.3)

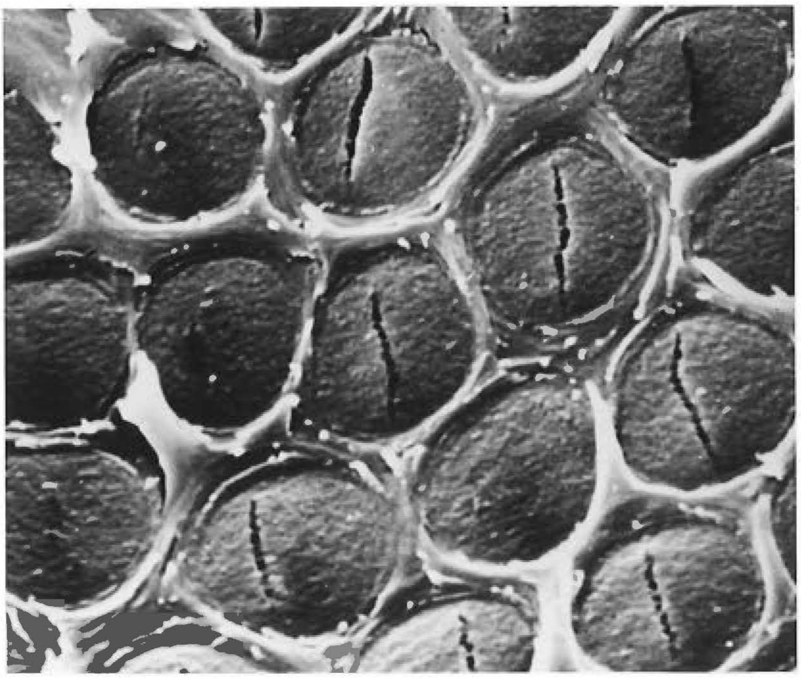


Figure 2.3 Split in vessel pits as observed by Cech, 1971 (13350 x magnification)

No major damage to ray-cells, fibres and/or vessel walls was observed in boards rolled at the 8.5% compression level, whereas at the 12.5% level damage was evident within these different cell-types, but no figures or micrographs were included in the text to confirm this observation. Cech concluded, that if an optimum 7 to 8.5% compression was to be applied, it should be feasible to follow this by a high temperature kiln-schedule, which reduces the drying time from 430 hours (as with the conventional mild-kiln schedule) to 200 hours or less. The quality of timber and degrade during drying should be equal to that obtained with the mild schedule.

Less positive results are reported in Cech's next publication, this time working with another species (Cech and Pfaff, 1975). Green boards (moisture content around 75 -85 percent) of Red oak <u>(Quercus rubra)</u> were rolled under compressions up to 7.5% but only insignificant reductions in drying time were recorded, from 17.5 to 16.5 days in conjunction with a mild accelerated kiln-schedule.

Compression rolling is also discussed in an unpublished report on the "effects of various pretreatments on the drying of red and hard beech" by Haslett and Kininmonth in 1975. A compression of 10 percent applied to green (moisture content between 80 and 110 percent), 25 mm thick boards of <u>Nothofagus fusca</u> and <u>Nothofagus truncata</u> caused end splitting during the process and severe internal checking and shearing of the grain in subsequent drying using a mild kiln-schedule. The damage was more pronounced in the denser wood of <u>N. truncata.</u> A further correlation seemed to exist between the degree of saturation at the time of rolling and the severity of this damage: this being more pronounced when the initial moisture content was higher Haslett, personal communication, 1983).In spite of the structural damage the rolling technique did not accelerate the drying rate to a significant extent for either of the two tested species. A later study by the same authors in 1976 on the "effects of various pretreatments on the drying of <u>Eucalyptus spp.</u>" produced similarly disappointing results; compression rolling of green boards of <u>Eucalyptus obliqua</u> and <u>Eucalyptus regnans</u> at the 10 percent level did not significantly accelerate drying. On the other hand, and in contrast to the findings with <u>N. fusca</u> and <u>N. truncata</u>, the technique did not produce severe end splitting, checking or other structural damage either during the rolling or in the course of the drying cycle.

Subsequently, in Australia, Campbell (1978) compression rolled green, backsawn boards of <u>Eucalyptus regnans</u> with the object of reducing collapse and checking which occurs with high-temperature kiln-drying schedules. His experiences showed no differences in drying behaviour between "rolled" boards and unrolled controls and he concluded by stating that "work to date appears to indicate that it confers no benefit".

In contrast to the optimistic statements and claims made earlier both in Goulet's patent and in the original publications (Goulet, 1968; Cech and Goulet, 1968; Cech, 1971), Berni and Christensen (1979) came to similar negative conclusions regarding the effects of dynamic transverse compression on internal checking during redrying of 45 mm, CCA (Copper, chrome arsenic) treated radiata pine sapwood . Contrary to Cech they found that compression rolling of freshly treated (nearly fully saturated) boards did not reduce internal checking when redried using high temperature schedules (kiln schedule: 120 ^{o}C dry bulb,70 ^{o}C wet bulb, air speed of 5.0 m/s). However a reduction in drying artifacts against controls were observed when seasoning "treated and rolled" boards using the conventional drying schedules. It is suggested here, that "...internal checking is principally related to the steepness of the moisture content gradients developed during drying, these being related to the severity of the drying conditions..." A high temperature kiln schedule is simply inappropriate when redrying CCA treated radiata pine.

Grozdits and Chauret (1981) in their discussion on the behaviour of wood structure during seasoning list several species previously compression rolled, although no specific information is given about the experimental procedures. The authors mention that hard maple (Acer saccharinum) and white birch (Betula papyrifera) had shown moderate improvements in "...drying characteristics..." without quantifying their statements; on the other hand aspen (Populus tremuloides) and spruce (Picea glauca) were not positively affected. They interpreted these observations in terms of differences in pit-membrane dimensions of the species mentioned. In the case of birch these were small in diameter and burst during deformation while the large window-like pits in aspen appeared to be stretched but not ruptured. No attempt was made to explain the causes for these differing patterns of damage shown in their accompanying figures.

2.3.2. Statement of the problem

The variability in results experienced by previous workers who have studied compression rolling does not allow meaningful or generalized conclusions to be made regarding the potential of the technique. In summarizing the research to date the following observations indicate why there are still doubts about the effectiveness and use of compression rolling, despite claims of very substantial improvements in both drying rate and timber quality after drying (Goulet and Cech, 1967; Goulet, 1968; Cech and Goulet 1968; Cech, 1971; Cech and Pfaff, 1975):

- These studies have been primarily concerned with the drying of hardwoods - except Grozdits and Chauret (1981) which do not go into much detail and Berni and Christensen (1979).
- Except in one case (Grozdits and Chauret, 1981) which which is not described in detail, only hardwoods have been investigated for the influence of compression rolling on drying.
- Except in one case (Berni and Christensen, 1979) the the technique has only been applied to fresh material.
- Only in two papers have the authors attempted to to relate the apparent influence of the rolling process to the anatomical characteristics of the timber (Cech, 1971; Grozdits and Chauret, 1981).
- There are contradictions in the published literature

regarding the degree of acceleration in drying even for a single species (Yellow birch), (Goulet 1968, Goulet and Cech 1968, Cech 1971).

- Disagreement exists regarding the effect of compression rolling on drying when differing drying schedules are applied (especially concerning the effects of high--temperature schedules).
- Little attention has been paid to the interaction between inherent anatomical wood characteristics and sap distribution during the dynamic compression and decompression cycle.
- The process proved to be unsuitable for more impermeable timber species such as New Zealand native beeches, Nothofagus fusca and Nothofagus truncata, (Haslett and Kininmonth, 1975) partly contradicting an earlier study on drying (Cech, 1971), which had indicated that compression rolling could have a more pronounced effect on less permeable wood.
- In most of the investigations only limited emphasis was placed on specific aspects of machine design and on the various process related parameters such as feed-speed, roller diameter and temperature.

2.4. EFFECTS OF COMPRESSION ROLLING ON THE TREATABILITY OF TIMBER

2.4.1. Summary of literature to date

Although there were no indications in the original patent (Goulet 1968) of the possible application of compression rolling to improve the treatability of timber, an investigation to verify this was undertaken by Goulet, Cech and Huffmann in 1968 . Green boards (moisture content between 30 and 50 %) of Eastern white spruce (Picea glauca) were subjected to compression levels between 5 and 20 percent while passing through 110 mm diameter rollers. In addition, one group was exposed to a subsequent 2.5 hour steaming treatment (wet bulb temperature: 100 ^{o}C). Both groups were then pressure treated with a 2.2 percent CCA solution according to an empty-cell Bethell schedule { Pressure cycle 100 psi (691 kPa) for 2 hours}. Improvements in uptake of the order of 25 percent were recorded for both "rolled" unsteamed boards and "steamed only" boards, compared to controls while a rolling treatment before steaming did not lead to an additional improvement in uptake. Strength tests indicated that steaming decreased strength properties of Eastern white spruce by 20 percent, whilst the rolling technique at the optimum compression level up to 15 percent did not effect the mechanical properties substantially. Thus compression rolling might be preferred to steaming as a method for improving CCA - preservative uptake.

Cech and Huffmann (1970) compared the results of the initial "..exploratory study.." (1968) with those obtained in a second investigation of CCA- preservative uptake. Flatsawn boards of Eastern white spruce heartwood were seasoned to 20 percent moisture content and subjected to compression levels between 2.5 and 15 percent; again one group of samples was then steamed at 100 ^{o}C. The results were similar to those of the initial trials and "...results indicate that a compression level of about 10 percent is required to obtain a retention comparable to that obtained by using a steam treatment prior to preservation ...". More surprising was the finding that higher preservative retentions were recorded after rolling lumber at 20% moisture content (a 12.5% compression was optimal) than when rolling green wood. In the former case "..average solution uptake of preservatives (solution strength: 2.2 percent) was increased by 51 percent {from 10.7 to 16.2 lb/cu.ft (from 171.39 to 259.5 kg/ m^3)} and the average cross-sectional area penetrated was increased by 36% (from 30.3 to 41.2% ..." The highest comparable figures for preservative retention and uptake for boards rolled at 30 % moisture content prior to pressure impregnation were recorded after a 17.5 percent compression rolling treatment, where "..average retention of preservatives was increased by about 29 percent {from 8.2 to 10.5 lb/cu.ft (from 131.4 to 168.2 kg/m^3)} and penetrated area by about 71% (from 15.3 to 26.2%)..". (Note: Retention data is expressed in terms of total weight of treatment solution absorbed). At 20% moisture content compression rolling caused a greater increase in retention than in penetration, whereas the opposite was true at 30% moisture content.

Neither of these publications (Goulet, Cech and Huffman, 1968; Cech and Huffman, 1970) contain an explanation for the observed improvements in preservative uptake after compression rolling at these low moisture contents.

A further investigation by Cech and Huffman (1972) examined the commercial practicability of impregnating spruce heartwood joists with coal-tar creosote using compression rolling. Green, flatsawn boards of Eastern white spruce heartwood were rolled at compression levels between 10 and 20 percent and then subjected to an empty-cell treatment with coal-tar creosote. Substantial improvements in uptake and in retention were obtained at the 15 percent compression level. The retention was increased by 62% from 3.4 lb/cu.ft for controls to 5.5 lb/cu.ft. (from 54.46 to 88.10 kg/m^3) whereas the average penetration was increased by 58% (Note: retention data is expressed in terms of treatment solution absorbed not average or minimum depth of penetration). They state that "...drying of spruce heartwood to an moisture content of about 20% prior to compression and preservation with creosote may result in a further increase in the average retention..." An examination of distribution of creosote within the boards revealed that penetration mainly ocurred in radial direction "...from both wide faces..." while edge (narrow face) penetration was not improved. The authors conclude that improvements in both retention and penetration of creosote preservative of compression rolled timber indicate :"..that the creosote impregnation of spruce heartwood may now be commercially feasible..".

A further extensive investigation (Cech, Pfaff and Huffman, 1974) on Eastern white spruce examined the influence of moisture content and dynamic compression in relation to the penetration, retention and disproportioning of copper, chrome and arsenic. Flatsawn, 44 mm thick boards of Eastern white spruce heartwood were conditioned at four different moisture contents (57, 25, 20 and 17 %) and subsequently rolled at one of four compression levels (0, 12.5, 15 and 17.5%). A full-cell CCA vacuum pressure treatment (-85 kPa vacuum for 20 minutes and 1400 kPa pressure cycle for 2 hours and 40 minutes) was then applied to all boards using a 3 percent aqueous solution of preservative. Dynamic compression applied at all four initial moisture content levels improved penetration and retention figures significantly, while not affecting the disproportioning of the elements. Increases in CCA-retention of 210 percent (from 0.2 to 0.62 lb/cu.ft. or 3.2 to 9.93 kg/m^3) were recorded for boards rolled at 17 percent initial moisture content and 17.5 percent compression (Note: The retention data are expressed in terms of dry weight of salts absorbed); at the same time radial penetration was improved by 280 percent (0.04 inches to 0.14 inches) and tangential penetration from 0.02 inches to 0.09 inches. However the authors point out, that the recorded improved penetrations were still below the requirements of preservation standards, even so "..the combined treatment could find applications for spruce that requires a heavy shallow impregnation of fire-retardant chemicals..".

Referring to unpublished reports of compression rolling experiments with Douglas fir heartwood, Nicholas (1973) emphasised that moisture content and grain direction are the main criteria for determining its effectiveness: "...Moisture content also influences the effectiveness of compression and better results are generally obtained at lower moisture contents." Significantly greater retention resulting when the compressive stress is applied in the radial rather then tangential direction provides additional support for Cech's theory that the effect is due to pit membrane rupture. In order to fracture the pit membranes, compression must occur in right angles to the planes of the membranes. One would expect this to occur when wood is compressed in the radial direction because the majority of the pits are located on the radial surfaces of the tracheids.."(Figure 2.4).

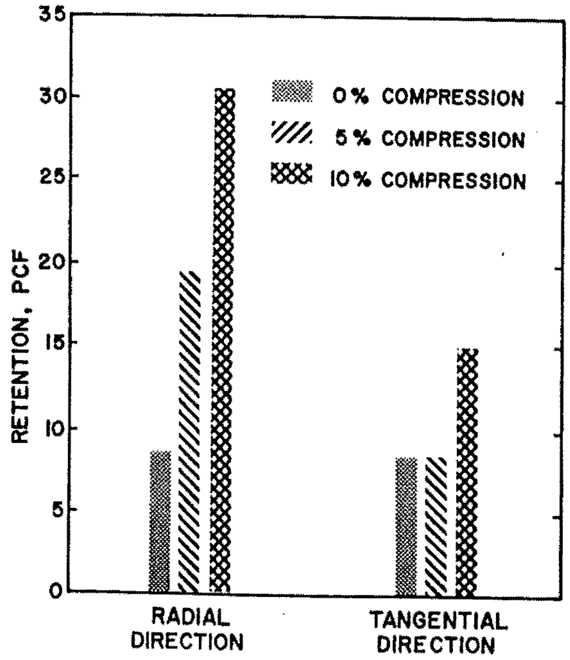


Figure 2.4 Histogram showing increase in preservative uptake in Douglas Fir heartwood (Nicholas, 1973)

Although offering a specific explanation for the improvements in permeability after compression rolling, the fact that detailed experimental material which lead Nicholas to his conclusions are not published make comparison with other work impossible.

A comprehensive study by Cooper (1973) compared the effects of compression rolling followed by various seasoning schedules and investigated their respective influences on the treatability of six conifers. Initially he determined the effects of compression rolling on the treatability of western hemlock (Tsuga heterophylla) sap and heartwood, without specifying either the rolling related parameters or the preservative treatment schedule. Conclusions drawn from these tests were:

- A substantial improvement of the treatability can be achieved by compression rolling
- A compression level beyond 10 % was of little or no advantage for further improvement on treatability

The object of the subsequent main experiment with coast Douglas-fir, interior Douglas-fir, western hemlock, amabilis fir, white spruce, and lodgepole pine was "...to quantify the improved preservative treatments that might be possible with precompression and various seasoning methods...". 200 specimens of each species were side-matched and half of these compression rolled at the 10 % compression level in the green condition (30 - 50 % moisture content). Controls and rolled boards were then subdivided into four groups of 25 boards, of which three groups were treated with creosote and one group was subjected to a commercial Bethell full-cell pressure treatment with a 2.2 % concentrated solution of CCA preservatives (mentioned in Table 2.2 below). Each of the groups to be preservative treated with creosote received a different seasoning pretreatment, to test the individual and interactive effects of a BUV- treatment (boiling under vacuum) and kiln-drying on treatability. The four groups were treated according to the following schedules:

<table>
<tr><th></th><th>Seasoning</th><th>Preservative Treatment</th></tr>
<tr><td>Group 1</td><td>Boiling under vacuum (BUV) applied to green wood</td><td rowspan="2">9 hr seasoning bath at 87.7 C and -85 kPa

3 hr creosote treatment at 87.7 C and 1470 kPa pressure.
1/2 hr expansion bath.
1/2 hr final vacuum at -71 kPa</td></tr>
<tr><td>Group 3</td><td>BUV applied to timber kiln dried to 10% moisture content by mild schedule</td></tr>
<tr><td>Group 2</td><td>Timber kiln dried to 10% moisture content by mild schedule</td><td>3 hr creosote treatment at 87.7 degrees Cent. and 1470 kPa pressure.
1/2 hr expansion bath.
1/2 hr final vacuum at 71 kPa</td></tr>
<tr><td>Group 4</td><td>Timber kiln dried to 10% moisture content by mild schedule</td><td>1 hr initial vacuum at -77.9 kPa.
1/2 hr flooding with a 2.25 % solution of CCA -77.9 kPa followed by a 14 hr pressure cycle at 1838 kPa</td></tr>
<tr><td>Additional group</td><td>BUV applied to green timber</td><td>10 hr seasoning bath at at 87.7 C and -85 kPa
7 hr creosote treatment at 87.7 .C and 2131 kPa pressure .C
3/4 hr expansion bath.
Final vacuum of -71 kPa</td></tr>
</table>

Table 2.2 Seasoning and preservative treatment schedule (according to Cooper 1973)

The results of the treatments applied to group 1, 2, 3 and 4 were compared in an analysis of variance (Table 2.3 = 3,4 and 5 of Cooper 1973) where the findings regarding the additional group were not included and are hence listed in a separate table (Table 5 of Cooper, 1973). Cooper summarizes his conclusions as follows:

- The results of compression rolling were not consistent, although in most cases a significantly better treatment was achieved, especially regarding minimum and average face penetration.

- The choice of a randomized block design proved to be a useful statistical method to establish that variability in the results was often due to between plank variability and not caused by the different treatments tested.
- CCA preservative penetration was generally deeper than creosote penetration, which was interpreted in part as due to the more severe CCA pressure treatment.
- The preservative penetration pattern varied between species and latewood treated better than earlywood with the exception of Amabilis fir and western hemlock.
- A significant improvement in creosote retention was achieved in compression rolled boards of western hemlock and lodgepole pine at the 10 % compression level, although a similar uptake improvement with CCA salts did not occur.

- Minimum face penetration in compression rolled (10 %) western hemlock and lodgepole pine was significantly improved by both preservative treatments.
- Average face penetration in 10 % compressed, creosote treated lodgepole pine, interior Douglas-fir and white spruce was significantly higher, but this was considered of no practical importance.
- Minimum and average face penetration in interior Douglas fir and white spruce were improved further with a combination of a higher precompression (15 %) and a more severe seasoning and subsequent creosote preservative treatment (Table 5 of Cooper, 1973).
- The improvement in treatment was limited to an increase in face penetration for both 10 % and 15 % compression level, although magnitudes of improvements were not of practical importance. In addition higher compression levels and harsher preservative treatment conditions caused extensive collapse in all species.

Table 3. — EFFECT OF COMPRESSION — CCA-TREATED LUMBER.

	Retention (pcf)			Min. face penetration (in.)			Avg. face penetration (in.)			Min. edge penetration (in.)			Avg. edge penetration (in.)		
	Compression %			Compression %			Compression %			Compression %			Compression %		
Species	0	10	p[1]	0	10	p[1]	0	10	p[1]	0	10	p[1]	0	10	p[1]
Amabilis fir	.783	.766	.627	.297	.430	.020	.447	.552	.154	.630	.524	.506	1.12	1.18	.685
Western hemlock	.584	.607	.328	.212	.265	.164	.305	.370	.098	.216	.205	.869	.425	.509	.330
Coast Douglas-fir	.421	.429	.768	.076	.080	.875	.148	.212	.143	.081	.041	.249	.430	.398	.792
Lodgepole pine	.237	.254	.268	.059	.091	.244	.244	.163	.062	.198	.049	.144	.264	.284	.825
Interior Douglas-fir	.197	.219	.399	.047	.051	.404	.082	.097	.426	.091	.089	.933	.121	.154	.672
White spruce	.189	.184	.433	.031	.038	.169	.066	.073	.445	.040	.042	.713	.099	.094	.670

[1]Probability that difference occurred by chance rather than compression treatment.

Table 4. — EFFECT OF COMPRESSION — CREOSOTE-TREATED LUMBER.

	Retention (pfc)			Min. face penetration (in.)			Avg. face penetration (in.)			Min. edge penetration (in.)			Avg. edge penetration (in.)		
	Compression %			Compression %			Compression %			Compression %			Compression %		
Species	0	10	p[1]	0	10	p[1]	0	10	p[1]	0	10	p[1]	0	10	p[1]
Amabilis fir	11.78	12.86	.096	.103	.164	.021	.285	.312	.359	.114	.175	.272	.562	.586	.674
Western hemlock	6.76	8.68	.0004	.053	.075	.141	.145	.224	.229	.082	.097	.641	.211	.278	.132
Coast Douglas-fir	6.78	7.77	.130	.078	.074	.935	.160	.176	.389	.113	.086	.551	.242	.194	.287
Lodgepole pine	3.70	4.86	.000	.011	.015	.037	.028	.045	.006	.017	.027	.163	.112	.149	.089
Interior Douglas-fir	1.22	1.30	.484	.011	.011	.773	.017	.021	.009	.012	.012	.549	.023	.023	.876
White spruce	1.42	1.60	.519	.010	.011	.469	.017	.021	.088	.012	.012	.951	.041	.036	.448

[1]Probability that difference occurred by chance rather than compression treatment.

Table 5. — EFFECT OF SEASONING SCHEDULE — CREOSOTE-TREATED LUMBER.

	Retention (pfc)			Min. face penetration (in.)			Avg. face penetration (in.)			Min. edge penetration (in.)			Avg. edge penetration (in.)		
	Schedule[1]			Schedule[1]			Schedule[1]			Schedule[1]			Schedule[1]		
Species	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Amabilis fir	12.15	12.36	12.46	.114	.178	.107	.258	.352	.286	.228	.132	.072	.554	.636	.532
Western hemlock	8.38	6.84	7.94	.058	.086	.054	.138	.194	.222	.067	.108	.093	.196	.291	.246
Coast Douglas-fir	6.84	6.44	8.55	.044	.087	.092	.124	.200	.179	.096	.084	.118	.162	.223	.228
Lodgepole pine	4.11	3.94	4.79	.016	.013	.011	.042	.044	.024	.032	.016	.017	.159	.102	.130
Interior Douglas-fir	1.22	0.98	1.58	.012	.010	.011	.024	.012	.022	.014	.010	.012	.032	.015	.022
White spruce	1.48	1.52	1.54	.012	.010	.010	0.23	.020	.015	.014	.010	.010	.036	.028	.051

[1]Those values underlined by discontinuous lines are significantly different at the 5 percent level, as determined by Duncan's new multiple range test; e.g., for western hemlock, Schedule I gave a significantly higher retention than Schedule II, but Schedule III retention was not significantly different from that of Schedules I or II.

For lodgepole pine, Schedules I and II retentions are significantly lower than those of Schedule III, but are not significantly different from each other.

For amabilis fir, there is no significant difference in retentions resulting from any schedule.

Table 2.3 Tables 3,4 and 5 summarize the results of the analysis of variance (according to Cooper,1973)

2.4.2. Statement of the problem

The overall impression of the investigations published to date regarding the influence of compression rolling on the treatability of the tested species, is that the technique does result in some improvements in preservative uptake. Even so reservations remain as to the effectiveness of the process especially with regard to uniform, deep penetration. Further little is known of the underlying reasons for any improvements in permeability which must, presumably, arise from anatomical and structural alterations. In summary it can be noted that:

- Studies have been confined exclusively to softwoods.
- With one exception (Grosditz, 1981) no interest has been shown in wood-anatomical alterations that might be responsible for the improvements in treatability.
- It is not certain why rolling wood at lower moisture contents is more effective in improving permeability.

2.5. GENERAL INDICATIONS ON THE POTENTIAL FOR COMPRESSION ROLLING

The following conclusions can be drawn from the experiments described so far:

- Compression rolling may improve drying of hardwoods but the results are contradictory
- Compression rolling appears to improve treatability of softwoods

- The optimal level of compression within the elastic range and subsequent effects show a great range of variation between species. It is difficult to make any generalizations.

The following table summarizes the experiments with Compression Rolling prior to the initiation of the project at the University of Canterbury

TABLE 2.4

EFFECTS OF COMPRESSION ROLLING ON SAWN TIMBER

GYMNOSPERMEAE - SOFTWOODS

Botanical Name	Abies amabilis	Picea glauca	Picea glauca	Picea glauca	Pinus contorta	Pinus radiata	Pinus strobus	Pseudots. menziesii	Pseudots. menziesii	Tsuga heteroph.
Common Name	Silver fir	Eastern w.spruce	Eastern w.spruce.	Eastern w.spruce.	Lodgepole pine	Radiata pine	Eastern w.pine	Douglas fir	Douglas fir	Western Hemlock
Density (kg/m^3)	430	430	430	430	400	400	380	500	500	460
Wood maturity	Heartwood	Heartwood	Heartwood	Heartwood	Heartwood	Sapwood	Heartwood	Heartwood	Heartwood	Heart-Sapwood
Grain orientation	Not consid.	Flat-sawn	Flat-sawn	Flat-sawn	Not consid.	Flat-sawn	Flat-sawn	Not consid.	Flat-quarter	Not consid.
Moisture cont. (%)	28 - 50	28 - 50	38.6	20	28 - 50	Dry,Redr.	50 -70	28 - 50		28 - 50
Permeability	Resist.	Resist.	Resist.	Resist.	Resist.	Permeable	Moderate resist.	Resist.	Resist.	Moderate resist.
Process (Dr.,Tr.)	Creosote CCA	Creosote CCA	Creosote	CCA	Creosote CCA	Drying HT-Drying	?	Creosote CCA	CCA	Creosote CCA
Roller Size (mm)	152.4	152.4	114.3	114.3	152.4	?	114.3	152.4	?	152.4
Feed Speed (mm/s)	253.3	253.3	253.3	253.3	253.3	140.0	253.3	253.3	?	253.3
Opt.Compr. (%)	10	10	15	12.5 - 17.5	10	10 - 20	8 - 12	10	15	10
Results and Observations	CCA uptake . signif. on faces. (no edge-penetration). EW > LW Satisfactory treatment	Creosote uptake improved. Face penetration improved. LW>EW Inadequat treatment with CCA	Increase Pen.58 % Ret.62 % upt.only surfacial (no edge) significant retention	3.5x increase in radial penetration,4.5x in tang. direction Uptake is a surface phenomena	Improved creosote face penetration CCA upta- uptake not improved LW > EW	Slight reduction in checks when rolled green.Not effective when dry rolled	Compression surface phenomena leads to stretch- of pit membranes	Improved creosote retention Face penetration increased collapse at CL>15% Uptake of CCA not improved	Uptake improved 400 % in flatsawn boards due to damaged pit membranes	Creosote uptake improved, substant. on faces. High compression leads to collapse
Authors and Date	Cooper 1973	Cooper 1973	Cech et all 1972	Cech et all 1974	Cooper 1973	Berni et all 1979	Grozdits e.a. 1981	Cooper 1973	Nicholas 1973	Cooper 1973
Country	Canada	Canada	Canada	Canada	Canada	Australia	Canada	Canada	USA	Canada
Remarks	Detailed Reference Apparent correlation:permeability and density. Influence of intraspecific variability, no explanation of mechanism	Detailed Rf,points out problems if CL>15% Indicates role of axial permeability	Detailed Reference notes role of unaspirated LW pits responsible for good LW-permeability. Suggested rolling at 20%MC. No explanations	Detailed Reference Indicates disproportion of CCA. Increased retention at lower MC. Problems if CL>15% No explanation of mechanism	Detailed Rf,(see col.2) Low treatment due to narrow LW layers No explanations of mechanism	Checking when redrying treated P.radiata cannot be prevented No explanations of mechanisms. Very limited infos	No Data about experim. methods. Conclusions based on unpubl. data	Very low uptake only on surface indicates that LW provides pathways, this causes low permebility(see column 2)	Conclusion based on unpublished data Very incomplete and short	LW>EW,uniform pe-. netration pattern. Detailed report (see column 2)

The following table summarizes the experiments with Compression Rolling prior to the initiation of the project at the University of Canterbury

TABLE 2.5

EFFECTS OF COMPRESSION ROLLING ON SAWN TIMBER

ANGIOSPERMEAE - HARDWOODS

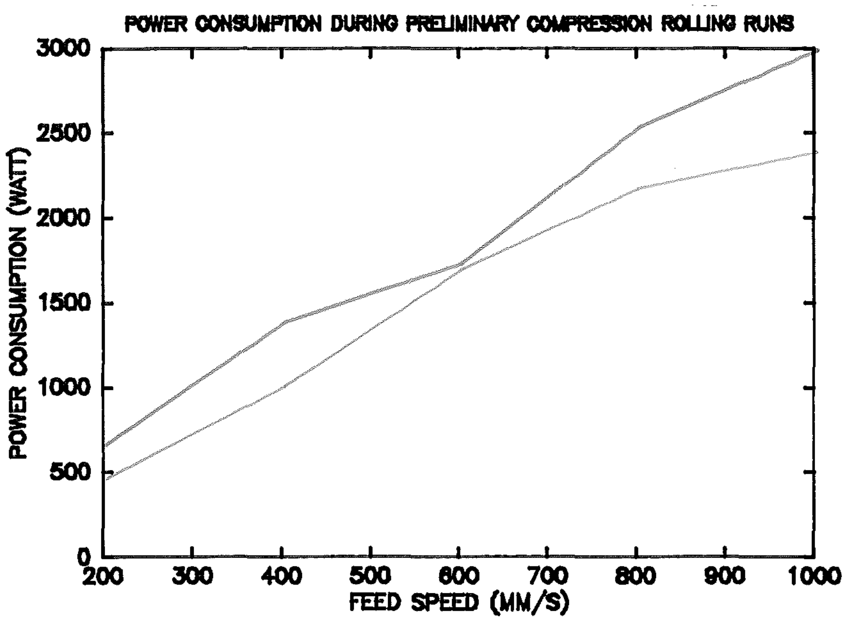
Botanical Name	Acer sacchar.	Betula alleghan.	Betula papyrif.	Eucalypt. obliqua	Eucalypt. regnans	Nothofag. fusca	Nothofag. truncata	Populus tremuloi.	Quercus rubra
Common Name	Hard maple	Yellow birch sp.	White birch	Messmate stringyb.	Mountain ash	Red Beech	Hard Beech	Trembling aspen	South. red oak
Density (kg/m^3)	610	640	540	490	700	530	600	450	650
Wood maturity	Heart-wood	Heart-wood	Heart-wood	Heart-wood	Heart-wood	Heart-wood	Heart-wood	?	Heart-wood
Grain orientation	Flat-sawn	Flat-sawn	Flat-sawn	?	Not consid.	Flat-sawn	Not consid.	Flat-sawn	Flat-sawn
Moisture cont. (%)	Green	Green	Green	Green 113.2	Green 110	Green 87.9	Green 85.3	Green	Green 80
Permeability	Permeable	Moder. Resist.	Moder. Resist.	Very resist.	Very resist.	Very resist.	Resist.	Resistant	Resist.
Process (Dr., Tr.)	Drying	Drying	Drying	Drying	Drying	Drying	Drying	Drying	Drying
Roller Size (mm)	114.3	114.3	114.3	50	?	50	50	114.3	114.3
Feed Speed (mm/s)	253.3	253.3	253.3	16.4	?	16.4	16.4	253.3	253.3
Opt.Compr. (%)	8 - 12	8.5 - 12.5	8 - 12	10	?	10	10	8 - 12	7.5
Results and Observations	Moderate improvement of depth of deformation during rolling	Possible to dry at high temperat. slight reduction drying time	Deep distribution of deformation in board. Pits damaged due to small size	No improv on drying time nor influence on shrinkage	No improvement on drying	Severe checks in 25% of boards, no decrease in drying time	Severe checks in 75% of bds, no decrease in drying time	No drying improvement. Pit membrane stretched no splits	Slight decrease in drying time, not of economic signific.
Author(s) and Date	Grozdits e.a. 1981	Cech 1971	Grosditz 1981	Haslett e.a. 1975	Campbell 1978	Haslett e.a. 1975	Haslett e.a. 1975	Grozdits 1981	Cech et all 1975
Country	USA	Canada	USA	N.Z.	Australia	N.Z.	N.Z.	USA	Canada
Remarks	Lacks detailed data. Indicates damage to pits improves drying through diffusion	21% increase in diffusion Evidence of shear and hydraulic pressure may rupture pit membranes	Lacks detailed data. Pit rupture accounts for high vapor diffusion Conclus. do not convince	Process not effective Machine not up to standard	Lacks detailed data. Main emphasis on other issues	Highly saturated boards may explain damage. Machine not adequate	Limited emphasis on rolling due to restrict. machine capacity	Stretched pit membranes not convincingly interpreted. Very limited data.	Lacks detailed data. Main emphasis on other issues

CHAPTER 3: THE COMPRESSION ROLLING MACHINE

3.1. ELABORATION OF MACHINE SPECIFICATIONS

A very simple compression rolling device, driven by a powered lathe, was used for preliminary test runs to establish the main criteria for the design of a multifunctional rolling machine. This was thought necessary since in earlier attempts to determine parameters such as power requirements and expected loads (Lawrence, 1980) substantial differences between the theoretically determined values and measured values had been observed.

The preliminary rolling experiments were designed to determine the influence of feed speed, compression level, board dimensions, density of timber and grain orientation on the torque requirements, which in turn gave an indication of the total expected power consumption. Two timber species (*Pinus radiata* and *Quercus robur*) were selected for the tests to establish difference in rolling conditions for a low density timber (*Pinus*) and for a denser timber (*Quercus*). Graph 3.1 illustrates the effects of density and feed speed on the power consumption during rolling of a 23 mm board while compressed to 85% of its original thickness.



Graph 3.1 Power consumption corresponding to <u>Quercus rubra</u>, (blue) and to <u>Pinus radiata</u> (gold)

On the base of these rolling experiments a set of specifications were elaborated for the design of the main rolling device and its power unit:

1. <u>Power requirements:</u> 18 kW

2. <u>Load between rolls:</u> 50 kN.
The compression of the denser timber under dynamic conditions induced loads up to 50 kN, which would need to be reacted by the frame.

3. <u>Roller dimensions:</u> 50 mm to 300 mm in diameter. Five roller sizes to be

	provided, with a minimum diameter of 50 mm and a maximum diameter of 300 mm. The minimum axle length of the rollers was to be no less than 200 mm to permit rolling of 150 mm wide boards
<u>4. Roller surface:</u>	Grooved infeed rollers. An increase in traction between between steel and wood was to be achieved by grooving the surface of the steel infeed rolls.
<u>5. Roller drive:</u>	Hydraulic drive. A drive system capable of driving the rollers at variable speeds and in both directions (0.1 m/s to 3 m/s)
<u>6. Adjustment of roller fixed gap and compression :</u>	All rolling tests were to be performed with a fixed gap, subjecting the timber to a constant preset compression. At the same time the system needed to accommodate without damage extreme, differences in load due to localized

variations in stiffness of the board (associated with knots), by provision of a safety mechanism to protect the machine against overloading. The roller gap must be accessible from at least one side to allow the installation of optical devices to monitor the process.

7. Load and power recording instrumentation :

To permit measurement of applied forces acting on the board during rolling, power consumption and feed speed.

8. Safety and protection :

The device had to be equipped with emergency stops,to protect it and its operator from accidents.It was further to be coated with a protective paint against the corrosive action of displaced sap from the rolled boards.

These specifications were incorporated in the design of the rolling device and its power unit, which was undertaken in collaboration with the School of

Engineering, who provided technical assistance during the design and the construction (Guenzerodt, Johnson, Whybrew and Walker, 1984). The Author wishes to acknowledge the contribution of Mr G.R. Johnson who designed the machine and of Mr Scott Amies, who manufactured the machine. The support of Mr Paul Fuller and Mr Rob Dalley from the School of Forestry who constructed the power unit is also acknowledged.

3.2. COMPRESSION ROLLING DEVICE

The completed machine is shown in Figures 3.1. and 3.2. It was designed to give control over all parameters considered to be important in compression rolling of timber and it was instrumented to monitor these parameters.

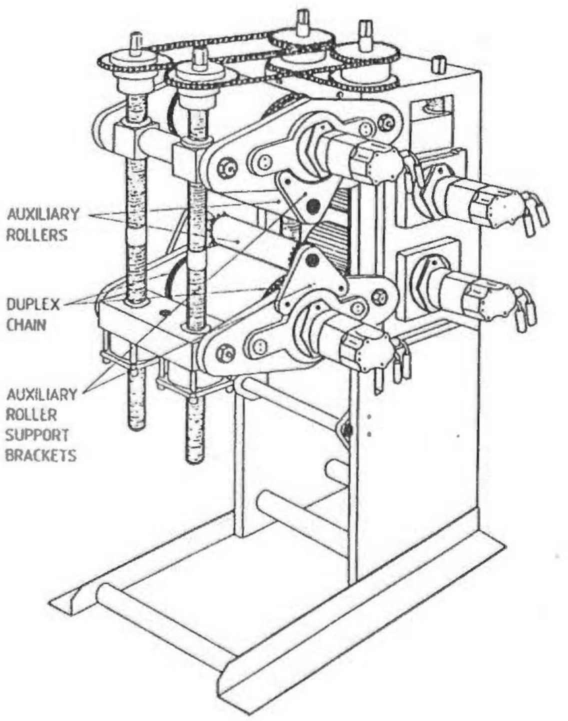


Figure 3.1 Compression Rolling machine with Auxiliary Rollers in Place

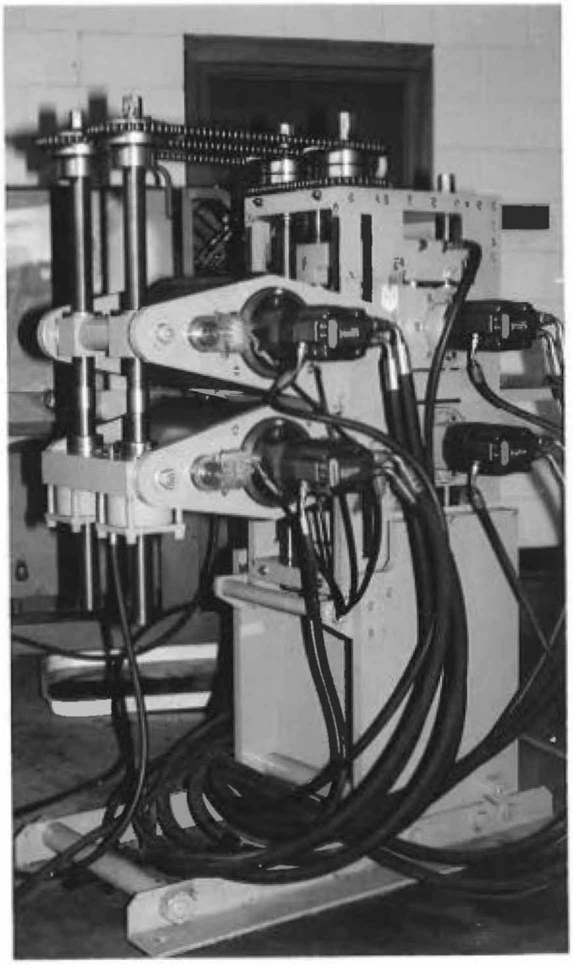


Figure 3.2 Compression Rolling Device

There are two pairs of rollers; a smooth pair of compression rollers and a grooved pair of infeed rollers. The infeed rollers are necessary because of the low coefficient of friction between wet wood and smooth steel, = 0.16 - 0.39 (McKenzie and Karpovich, H., 1968). Each roller is driven by a hydraulic motor which is connected to a variable displacement pump; the piping through a multiple port manifold is linked in such a manner, that the two roller-pairs can be controlled independently.

The lineal feed speed can be continously varied from 0 to 3 m/s and is monitored by two digital display tachometers. The maximum speed that can be achieved depends on the dimension of the timber to be rolled, the degree of compression, the board thickness and the roller size. The limiting factor is the power available (nominally 18 kW). During rolling the work done on the wood is a function of feed speed and the volume of wood being deformed by the rollers. Board sizes up to 140 mm in thickness and 110 mm in width can be accomodated with compressions up to 20 % . The maximum design compression force is 100 kN. To enable torque to be monitored the compression roller motors are reacted by dynamometer elements: The roller axles are supported by load beams with callibrated strain gauges attached which enable the compressive force and torque to be monitored. The construction of the machine differs from conventional rolling mill design in that the compressive force is not applied by the external frame of the machine but by direct tension in the 4 load screws which link the bearing supporting structure for each roller pair. This configuration has the advantage of not needing a heavy external structure. The load screws, which are of necessity very long to accomodate the auxiliary rollers, can be comparatively slender since they are not subjected to buckling loads as would be the case with a conventionally designed rolling mill. With this configuration, the compression rollers are left unenclosed with good access to the nip area for photography and board thickness measuring instrumentation. The set of 4 load screws for each roller pair are reverse threaded, top and bottom, and linked by a chain and sprocket system to give easy and convenient adjustment of the roller gap and hence compression of the board. Knots in the wood are considerably stiffer than the surrounding timber and when applying large compressions protection must be provided to prevent damage to the machine and to avoid the knot fracturing. The compression rollers have an hydraulic cross-head for one of the pairs of screws. The nuts on this pair of screws are loaded against stops by hydraulic pressure from an auxiliary pump. Overload protection is achieved by a relief valve in this hydraulic circuit. Once the stiffer region associated with the knot passes into the roller gap the rollers automatically open and then return to their preset gap once the knot has passed through the rollers. Similar provision is made for the infeed rollers.

Roller diameter is expected to be another important parameter and it was important to be able to change the compression roller pairs easily. Smaller diameters are achieved by fitting auxiliary rollers as shown in Figure 3.1. These are friction and sprocket driven by the main rollers which then act as back-up rollers, enabling very small auxiliary rollers to be used without bending. A positive chain drive is also provided by back driving using a duplex chain. It is of course necessary to reverse the direction of rotation of the main compression rollers but the lineal speed range is not affected by changing the auxiliary roller diameter. Larger diameters can also be provided by fitting solid sleeves over the main compression rollers. In this manner a range of diameters from 51.8 mm to 300 mm is available.

3.3. POWER UNIT

The power unit is equipped with a three-phase 18 kW electric motor. The slip ring starter was replaced by an inline resistive starter to protect the main power supply from overload. The motor drives a pair of variable displacement hydraulic oil pumps through a triplex chain-sprocket connection. The two pumps are piped into a multiport manifold, which acts as an interface between pumps and the four hydraulic motors which in turn drive the four rollers. The manifold regulates the oilflow to the motors and so can manipulate the power available to the two roller pairs (infeed and compression rollers). It is equipped with a high pressure relief valve to protect the pump from overload.

The selection of a hydraulic drive system had the following advantages over gear driven or belt driven rolling equipment:

- Infinitely variable feed speed
- The ability to speedily change both speed and rolling direction
- Separate control of the two roller pairs offering independent speed variation between infeed and compression rollers. And most important, the ability to concentrate power on a single roller pair if required
- Supply of hydraulic overload protection against knots

3.4. GENERAL FEATURES

The total of sixteen strain gauges installed on the four torque arms were connected in pairs and wired up in a half-Wheatstone bridge with temperature compensating circuits to monitor loads and torque during rolling, as illustrated in Figure 3.3:

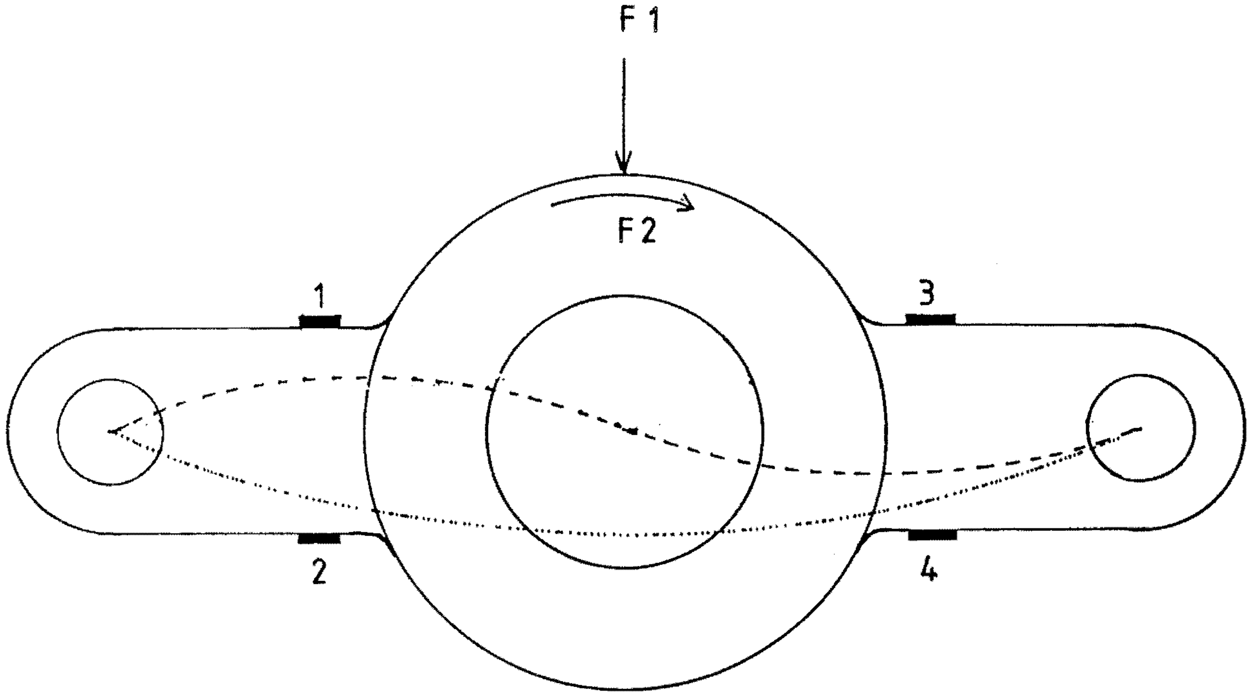


Figure 3.3. Schematic representation of the lower torque arm with four strain gauges (1 - 4) attached as shown. The dashed line (- - - -) is in the plane of the of the torque arm, the dotted line (......) is a deflection of the beam about the horizontal axis at the mid point of the torque arm

During rolling the beams are subjected to a combination of force F 1 and torque F 2; F 1 represents the force component induced by the compression of the board. The beam deflects vertically which results tensile strains in strain gauges 2 and 4 and compressive strains in strain gauges 1 and 3. The applied torque, represented by F2 (Figure 3.3) is reacted in the beam, which is consequently deformed into an S - shape. This deformation induces tensile strains in the strain gauges 1 and 4 and compressive strains in strain gauges 2 and 3. The separation of signals coming from the four strain gauges is achieved with the half bridge circuit, where gauges 1 and 2, and gauges 3 and 4 are connected in pairs, equivalent to R1 and R2 in the following wiring diagramm, (Figure 3.4):

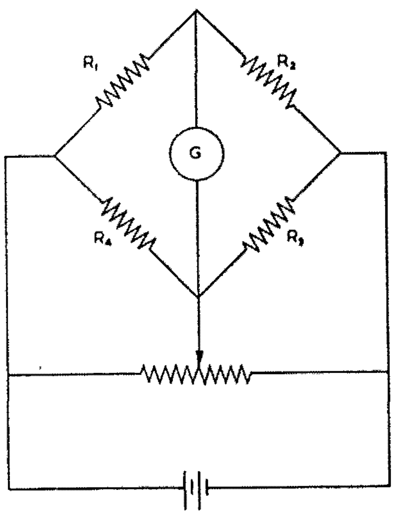


Figure 3.4. Half - Wheatstone bridge circuit with temperature compensation as recommended for beams in bending (according to Hearn , 1971)

The bending effects being opposite in sign will produce a signal in the galvanometer where the resultant reading represents the sum of the strains in the two corresponding strain gauges:

$$+\varepsilon_{B1} - (-\varepsilon_{B2}) = 2\varepsilon_B \qquad \text{(Equation 3.1.)}$$
$$+\varepsilon_{B2} - (-\varepsilon_{B4}) = 2\varepsilon_B \qquad \text{(Equation 3.2.)}$$

ε_{B1} = Strain in strain gauge 1 due to bending
ε_{B2} = Strain in strain gauge 2 due to bending
ε_{B3} = Strain in strain gauge 3 due to bending
ε_{B4} = Strain in strain gauge 4 due to bending
ε_B = Mean bending strain

Hence during loading under conditions of pure bending, the signals (or changes in resistance) from each of the four strain gauges can be added and averaged to determine the mean bending strain:

$$(\varepsilon_{B1} + \varepsilon_{B2} + \varepsilon_{B3} + \varepsilon_{B4})/4 = \varepsilon_B \qquad \text{(Equation 3.3)}$$

On the other hand where only a torque F2 acts on the torque-arm strains in the four gauges will be distributed as follows:

$$\varepsilon_{T1} + \varepsilon_{T2} = \varepsilon_T \qquad \text{(Equation 3.4.)}$$

$$\varepsilon_{T3} + \varepsilon_{T4} = \varepsilon_T \qquad \text{(Equation 3.5.)}$$

ε_{T1} = Strain in strain gauge 1 due to torque
ε_{T2} = Strain in strain gauge 2 due to torque
ε_{T3} = Strain in strain gauge 3 due to torque
ε_{T4} = Strain in strain gauge 4 due to torque

The signals can be added and averaged to determine the mean strain induced by torque:

$$(|\varepsilon_{T1}| + |\varepsilon_{T2}| + |\varepsilon_{T3}| + |\varepsilon_{T4}|)/4 = \varepsilon_T \qquad \text{(Equation 3.6)}$$

During compression rolling, the bending and torsional forces act together and a superposition of strains occur in the strain gauges. These can be separated as follows, assuming symmetrical conditions in the torque arm and identical deflections of the strain gauges:

$$|\varepsilon_{B1}| = |\varepsilon_{B2}| = |\varepsilon_{B3}| = |\varepsilon_{B4}| = |\varepsilon_{B}| \qquad \text{(Assumption 1)}$$

$$|\varepsilon_{T1}| = |\varepsilon_{T2}| = |\varepsilon_{T3}| = |\varepsilon_{T4}| = |\varepsilon_{T}| \qquad \text{(Assumption 2)}$$

$\varepsilon_1 = \varepsilon_{B1} - \varepsilon_{T1}$	$\varepsilon_{B1} = \varepsilon_1 + \varepsilon_{T1}$	$\varepsilon_{T1} = \varepsilon_{B1} - \varepsilon_1$
$\varepsilon_2 = \varepsilon_{B2} - \varepsilon_{T2}$	$\varepsilon_{B2} = \varepsilon_2 + \varepsilon_{T2}$	$\varepsilon_{T2} = \varepsilon_{B2} - \varepsilon_2$
$\varepsilon_3 = \varepsilon_{B3} + \varepsilon_{T3}$	$\varepsilon_{B3} = \varepsilon_3 - \varepsilon_{T3}$	$\varepsilon_{T3} = -\varepsilon_{B3} + \varepsilon_3$
$\varepsilon_4 = \varepsilon_{B4} + \varepsilon_{T4}$	$\varepsilon_{B4} = \varepsilon_4 - \varepsilon_{T4}$	$\varepsilon_{T4} = -\varepsilon_{B4} + \varepsilon_4$

(ε_1= Combined strain from bending and torque in gauge 1
(ε_2= Combined strain from bending and torque in gauge 2
(ε_3= Combined strain from bending and torque in gauge 3
(ε_4= Combined strain from bending and torque in gauge 4

$$(\varepsilon_{B1} + \varepsilon_{B2}) + (\varepsilon_{B3} + \varepsilon_{B4}) = \varepsilon_B \times 4 \qquad \text{(Equation 3.7.)}$$

$$(\varepsilon_{T1} + \varepsilon_{T2}) - (\varepsilon_{T3} + \varepsilon_{T4}) = \varepsilon_T \times 4 \qquad \text{(Equation 3.8.)}$$

Hence a separation of the torque induced strain from the bending strain can be achieved by substracting the signals from gauges 1 and 2 from those of gauges 3 and 4 (or viceversa, Equ. 3.8.), to give a measure of the torque, whereas the total bending strain is obtained by adding all four strain gauge readings thereby eliminating the torque induced strain component (Equ. 3.7.).

The strain gauges were calibrated under static test conditions (steady state), simulating the compressive forces and the torque separately.

3.5. LIMITATIONS

Although the design and the construction of the rolling device was based on preliminary test runs and on the experiences of other workers with compression rolling equipment (Cech,1981 personal communication), the data base was clearly inadequate. Early workers provided minimal technical information, while our own earlier prototype was not able to explore the full range of capability desired in the machine to be built. The initial rolling runs to test the performance of the machine revealed the certain inadequacies or limitations:

1. The total power available to drive the four rollers was insufficient. There were substantial power losses in the transmission between electric motor and hydraulic pump, and within the hydraulic system. A partial solution has been to shorten the hydraulic hoses, to connect motor pairs in series and so minimize power losses within the manifold. These alterations increased power available considerably although there is less flexibility in operation.

2. The initial deflection of the compression rollers during the rolling cycle was too great, due to the three deflection components:

- Backlash within the main frame
- Insufficient restraint between rollers and roller supporting beams
- Insufficient stiffnes of the torque arms (beams), leading to excessive deflection in both horizontal and vertical planes.

In an initial attempt to decrease the amount of flexing the upper and lower torque arms were stiffened by connecting horizontal brackets, but this only reduced flexure slightly. A further redesign of the dynamometer elements is in progress.

3. The deflection of the torque arm in bending was substantially greater than that caused by the torque reaction, hence the strain signals could not be separated accurately. The present redesign of the torque arms also takes this into account, by separating the torque measurement completely from the three-point bending as illustrated in Figure 3.5.

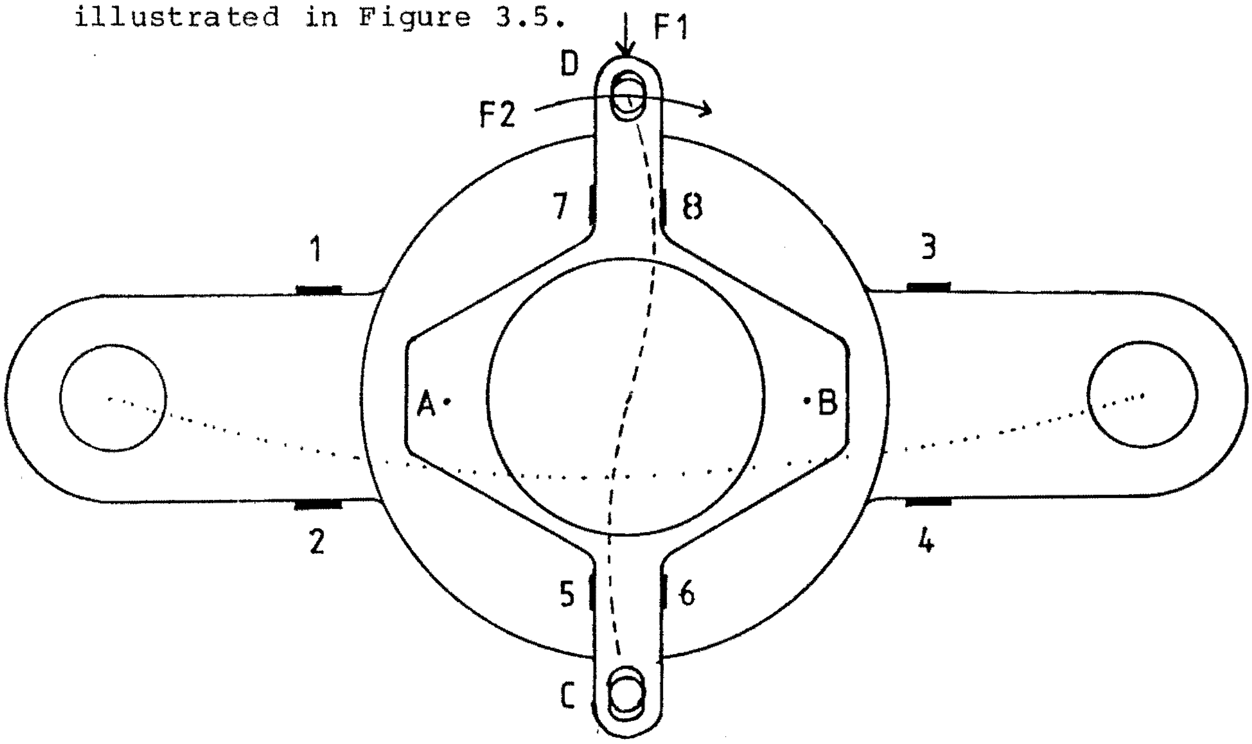


Figure 3.5 Scheme of redesigned torque arm

The results of the main rolling programm with "green" boards of Red Beech were affected by these factors. Insufficient power at high compression levels and large roller diameters did not allow rolling at high feed speeds and in the subsequent multifactorial analysis of variance the feed speed had to be excluded. The effects of feed speed were established in a separate experiment.

The inaccuracy in performance of the torque arms did not allow the recording of reliable results concerning loads and power consumption during rolling. Consequently it was not possible to draw conclusions regarding interactions between the performance of the machine and the implications for the rolled material. Experience with the dynamometer elements was considered in a redesign, which is now completed and ready to be installed on the device.

The new design consists of two separate dynamometer elements:

- The load beam, of similar shape and installed in the same manner as the original torque arm. It is used to measure the compressive forces acting between the rollers and so the compressive stress acting on the timber during rolling.Strain gauges were installed on the four load beams (Figure 3.5.: strain gauges 1,2 3 and 4) and connected in half-Wheatstone bridge circuits (see Figure 3.4). The calculation of mean bending strain ε_B uses Equation 3.7., whereby eventual strain due to torque cancels:

$$(\varepsilon_1 + \varepsilon_2) + (\varepsilon_3 + \varepsilon_4) = \varepsilon_B / 4 \qquad \text{(Equation 3.9.)}$$

where

$\varepsilon_1, \varepsilon_2, \varepsilon_3 + \varepsilon_4$ are bending strain in strain gauges 1,2,3 and 4 respectively

- The torque is measured with only two vertical torque arms, one attached to each of the hydraulic motors at A and B, while at the same time being connected to the main frame through simple supports at C and D. A and B are fixed supports designed to carry loads in all three planes. The deformation of the torque arm during compression rolling is similar to the "S"-shape type deflection of the original torque arms, although the amount of deflection is expected to be substantially greater due to the smaller dimension. The torque arm is installed vertically to reduce bending moments to a minimum. Strain gauges are installed on spots 5,6,7 and 8 connected in half Wheastone bridge circuits in couples 5 - 6 and 7 - 8. The mean strain due to torque acting on each of the two torque arms can be determined by:

$$(\varepsilon_5 + \varepsilon_6) - (\varepsilon_7 + \varepsilon_8) = \varepsilon_T / 4 \qquad \text{(Equation 3.10)}$$

where

$\varepsilon_5, \varepsilon_6, \varepsilon_7 + \varepsilon_8$ are torque strain in strain gauges 5,6,7 and 8 respectively

CHAPTER 4: MATERIAL AND METHODS

4.1. TIMBER SELECTION, PREPARATION AND RANDOMIZATION FOR EXPERIMENT WITH NOTHOFAGUS FUSCA AT HIGH INITIAL MOISTURE CONTENT

Two similar logs of mature Red Beech (*Nothofagus fusca*) were selected from a stand in Maimai State Forest on the West Coast of the South Island of New Zealand. After milling a total of sixteen squares (dimensions: 100mm x 100mm cross-section) were selected from each log, avoiding pith, sapwood and defective areas (decay, pin-hole, discoloured wood etc). The squares were wrapped in heavy plastic immediately after sawing, transported to the laboratory within two weeks and stored in a cold room at $1^{o}C$. This procedure was necessary to avoid any moisture loss, since one of the basic requirements in the experimental layout was freshly felled green timber.

From the 16 beams, 240 replicates were cut (half quartersawn and half flatsawn), planed and reduced to their final dimension:

Length 650 mm
Width 100 mm
Thickness 25 mm

The replication was laid out considering inter- and intraspecific variability; hence two replicates, one from the upper and one from the lower part of each log were chosen for a fourfold replication of each treatment. The controls were obtained in the same way.

The preparation and allocation of the samples to different treatments followed a random selection as shown in Figure 4.1 :

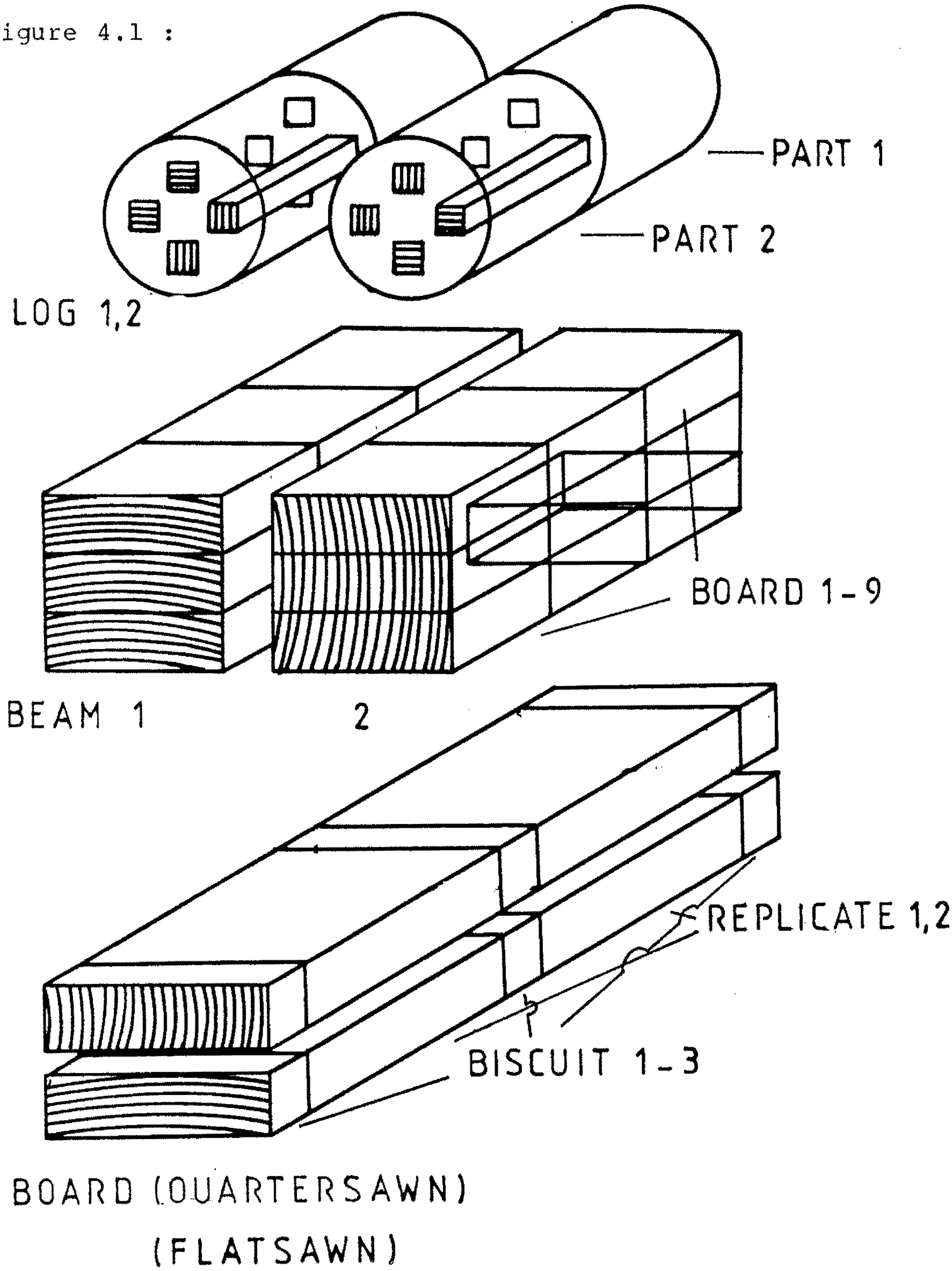


Figure 4.1 Specimen preparation

A numerical identification system was adopted to facilitate efficient data-processing and computing. Each board was given a five digit number, representing its individual treatment. The following treatment factors were chosen for the experiment (Table 4.1):

Digit	Treatment Factor	Number	Values
1st	Roller Diameter	1 2	50.6 mm 206.8 mm
2nd	Compression Level	1 2 3	7.0 % 10.0 % 13.0 %
3rd	Feed Speed	1 2 3	800 mm/s 1600 mm/s 2400 mm/s
4th	Grain Orientation	1 2	Quartersawn Flatsawn
5th	Replicate	1,2,3,4	N.A.

Table 4.1 Selection of treatment factors for multifactorial experiment with highly saturated boards of <u>Nothofagus fusca</u>

Thus a flatsawn replicate which was rolled between 50.6 mm rolls under a 10 % compression and at 2400 mm/s would be labelled 12321,12322,12323 or 12324 depending on which of the four replicates was referred to. Controls were labelled with four digit identifiers which characterized their location within the two logs, grain orientation and control number.

144 replicates were subsequently compression rolled in the green condition. The replicates to be rolled were

weighed immediately before and again afterwards. Half of all replicates were photographed during the compression cycle to determine the strain distribution within the boards, (see chapter 4.4.1. and 4.4.2.). Nine flatsawn and nine quartersawn replicates were kept as controls.

4.2. HOT WATER SOAKING PRETREATMENT

An additional 32 samples were subjected to a 20 - hour hot water pretreatment at 90 ^{o}C. 24 of these boards were compression rolled while hot and then wrapped in polyethylene bags together with the remaining 8 samples, which were hot soaked but not compression rolled. Subsequently all samples were dried under controlled conditions.

The hot soaking treatment was conducted as a separate experiment and was not included into the multifactorial experiment on the effects of rolling on green <u>Nothofagus fusca.</u> Only two factors besides the hot soaking pretreatment itself were tested, comprising three compression levels (7%, 10% and 13%) and two grain orientations (quartersawn and flatsawn).

4.3. PREPARATION OF TIMBER FOR SUBSEQUENT EXPERIMENTS

4.3.1. <u>Nothofagus fusca</u> partially seasoned to 60% moisture content

An additional log of <u>Nothofagus fusca</u> was chosen from a stand in the Mai-Mai forest, milled and a number of selected squares shipped to the laboratory. Boards were cut from these squares and matched as before (see section 4.1). 40 flatsawn replicates and 40 quartersawn replicates were then selected for a further experiment to establish the effects of compression rolling a medium saturated timber (50 % saturation) on diffusivity and permeability. All replicates were air dried to an average moisture content of 60% (+/- 10%), before being stored in heavy plastic for two weeks. 64 replicates (32 quartersawn and 32 flatsawn) were then rolled with the large roller (206.8 mm) and at constant compression level of 10%. Besides grain orientation, the influence of feed speed was studied in this test and so the 64 replicates were subdivided into four subgroups of eight flatsawn and eight quartersawn replicates each to be rolled at one of four different feed speeds: 500 mm/s, 1000 mm/s, 2000 mm/s and 3000 mm/s. The remaining 8 flatsawn and 8 quartersawn replicates were kept as controls. All replicates were then stockpiled in a constant climate room at 24 ^{o}C and 65% relative humidity and weight losses recorded at weekly intervals, until moisture content of all samples had fallen below fibre saturation (method as described in 4.5.).

One half of all replicates (four flatsawn and four quartersawn samples from each feed speed subgroup) including half of the controls were subsequently prepared for a pressure treatment with CCA preservatives (method as described in 4.6.). The remaining 40 replicates were set aside to test the effects of rolling on the strength properties, which were established with a three-point bending test (according to the British Standards No. 373).

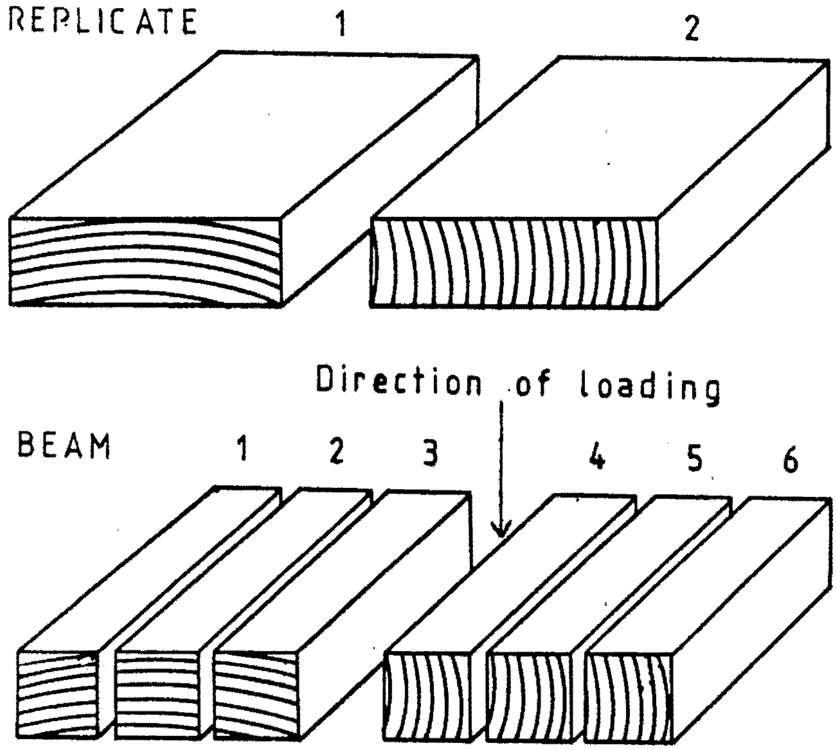


Figure 4.2 Selection of samples to determine the bending strength for rolled and unrolled replicates

All samples for strength testing were stored in a constant climate room set to equilibrate at 12 %. Subsequently three beams from each board were prepared. The boards were not planed or dressed as that would remove surface material which may have been damaged during compression rolling, and the tests were designed to "pick up" loss in strength in the regions of the surface. Two beams were allocated to a three point bending test and the remaining beam will be utilized to establish wedge hardness at a later stage. An Instron test machine model 1195 with a synchronized X/Y -chart recorder was used for all tests, which were conducted at constant climatic conditions of 20 ^{o}C and 40% relative humidity.

Bending Tests: A total of 80 beams, 64 of them compression rolled at four feed speeds and 16 controls were subjected to a three - point bending test (British Standards No 373, Princess Risborough 1969) after preparation to their final dimensions: 300 mm length by 23 mm in width and 23 +/- 1 mm in thickness. Crosshead speed was set at 0.11 mm/s. Stress/strain relationship of the beams was recorded on the X/Y recorder and the resulting graphs were analysed to determine the modulus of rupture, modulus of elasticity and toughness using a digitizer board (Digitablet, Numonics). Graph interpretation and calculations were done with a software interactive programme written for the connected Sirius computer. An analysis of variance was performed on all three strength test parameters.

4.3.2. _Nothofagus fusca_ seasoned to 20% moisture content

A number of boards from the original two logs of _Nothofagus fusca_ were air dried to around 20 % moisture content. Sixteen flatsawn replicates were subsequently prepared (dimensions as in 4.1.) to establish the effects of dynamic compression on timber at a moisture content below fibre saturation.

Twelve replicates were compression rolled, four at each of the three selected compression levels: 7% , 10% and 13% , while four replicates were kept as controls. The effects on permeability were assessed in a subsequent pressure treatment with CCA preservative (see method described in 4.6.). The small number of replicates did not allow conclusive statistical analysis of the results, hence interpretations of the experiences made in this experiment can not be generalized.

4.3.3. Experiments with alternative species

In addition to the comprehensive experiments with Nothofagus fusca, two other species were compression rolled with the modified device, in order to establish the effects of rolling on timbers having different anatomical characteristics. Dynamic compression was applied to Picea sitchensis heartwood (at 20% moisture content) and Pseudotsuga menziesii (heartwood and sapwood at a moisture content of aproximateley 20%).

PICEA SITCHENSIS: Boards were prepared from squares cut from two logs selected from stands near Conical Hill sawmill in the South Island of New Zealand. All boards were air dried to aproximately 20% moisture content and 32 replicates (16 flatsawn and 16 quartersawn; dimensions as described in 4.1.), were rolled (150.8 mm diameter rollers, at a constant feed speed of 1000 mm/s. The selected levels of compression, 6% , 9% and 12% , took account of the experiences of other workers, (Cech, 1971; Cooper, 1973). The assessment of eventual changes in permeability was based on the response of the boards to a pressure treatment with CCA preservatives (chapter 4. 6.). Samples from deformed areas near the surfaces of the boards were examined in the scanning electron microscope.

PSEUDOTSUGA MENZIESII :

A small number of boards of <u>Pseudotsuga menziesii</u> had been prepared in order to test the performance of the machine prior the initiation of the main experiment with red beech. Boards of thicknesses between 20 and 30 mm and constant width of 100 mm were rolled at compression levels varying between 5% and 15%, to collect information regarding machine performance and to note the important factors to consider in subsequent experiments. The boards were then pressure treated with CCA preservatives (chapter 4.6.) and samples prepared for microscopic examination.

4.4. TECHNIQUES FOR ANALYSIS OF DEFORMATION

4.4.1. Method of marking

It was intended to closely monitor the compression and decompression cycle during the rolling process. Grid pattern application techniques, such as described in the literature (Hoadley, 1968; Peters, Zenk and Mergen, 1968; McKenzie, 1969) were initially considered. Nonetheless disadvantages concerning the complexity of these methods as well as the long period of sample preparation made them impracticable for the present study: bear in mind the wood was still green in parts of the experiment. A grid pattern of overlapping circles (Spackman, 1975) was selected and photo-etched onto a zinc plate. The etched plate was then glued to an aluminium block using a two - component epoxy-resin adhesive (Figure 4.3). Subsequently a water soluble printing ink could be applied to the plate as a thin coat, using a hard-rubber roller and the plate pressed on the edge of carefully planed boards for a short period (5 - 10 s). The imposed surface grid pattern permitted qualitative and quantitative analysis of the deformation and strain distribution in the wood.

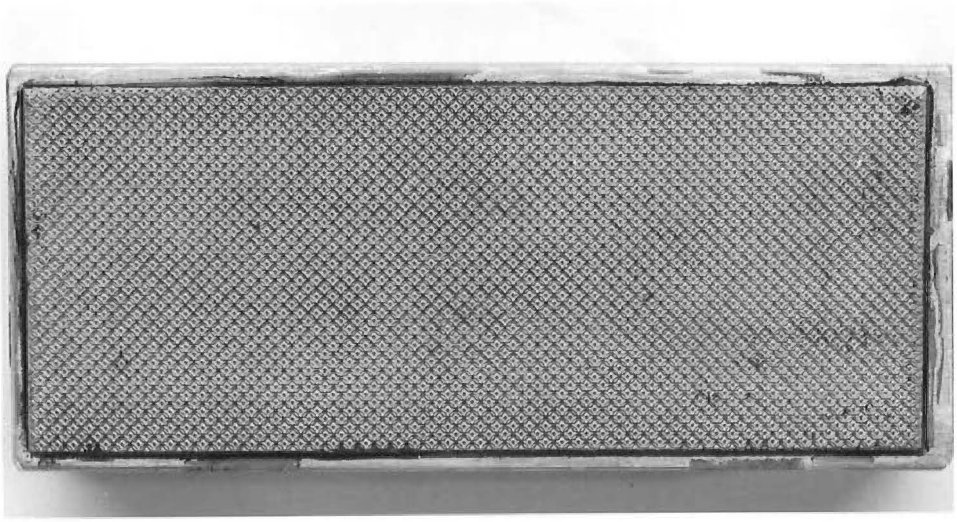


Figure 4.3 Photo-etched plate with grid pattern of overlapping circles

4.4.2. Photographic method

A 35 mm camera (Olympus OM1 with an Auto Bellows lens system for macroscopic 80 mm Olympus macro lens for macroscopic work), equipped with two synchronized flash units (Mecablitz 216 and Mecablitz 34 BCT2 L27CR) to provide a balanced light source, were located on the accessible side of the compression rollers (Figure 4.4). The distance between lens and board edge varied between 90 and 150 mm and the short duration of flash, 1/20000 s, "froze" the motion of the boards, which were travelling through the rolling machine at speeds up to 3000 mm/s. A nominal exposure time of 1/60 s and lens aperture of f 32 were used with a black and white film (Ilford F4, 125 ASA).

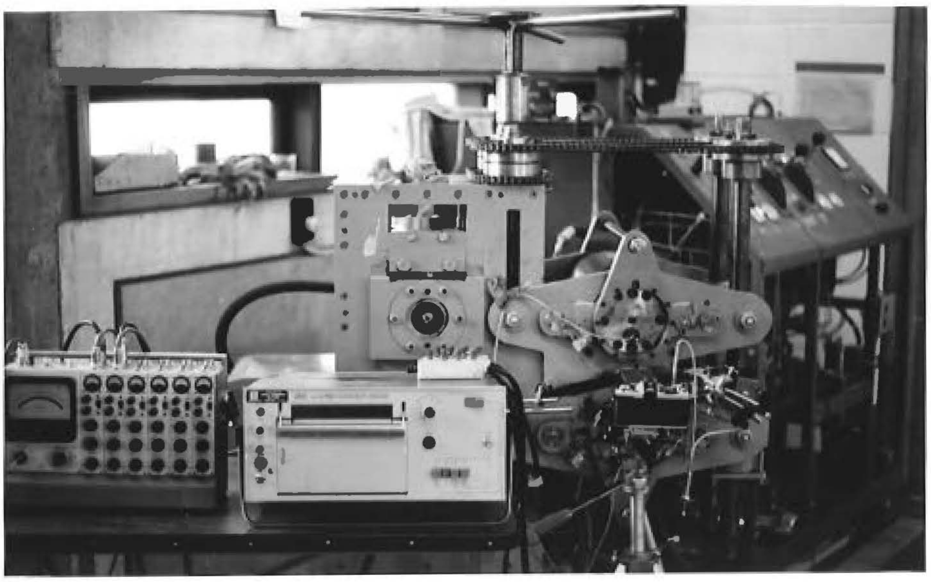


Figure 4.4 Installation of camera at the gap between the compression rollers

4.5. DRYING PROCEEDURES

4.5.1. Board preparation

The initial moisture content and green density of each replicate was determined from biscuits (20 mm x 20 mm x 100 mm) cut from each board as illustrated in Figure 4.1. Moisture content was calculated using the oven-dry method (ASTM D 2016, 1983), while green density was determined by the water displacement method (application of Archimedes principle, ASTM D 2016, 1983) ;

4.5.2. Drying environment

All replicates were endcoated with two layers of a two-component epoxy resin adhesive (Brandname: "Boscrete") and left 8 hours to cure before being transfered to a constant climate room and fillet stacked. The environmental conditions during drying to the desired moisture content at fibre saturation were set as follows (Table 4.2):

	DRY BULB (°C)	WET BULB (°C)	RELATIVE HUMIDITY (%)
DAY 1 - 4	19.0	18.5	95 - 100
DAY 4 - 28	24.0	23.0	90
DAY 28 - 49	25.0	22.5	84
DAY 49 - 60	26.0	23.0	78
DAY 60 - 68	27.0	23.0	74
DAY 68 - 72	29.0	25.0	68

Table 4.2 Drying schedule in the constant climate room

The very mild schedule was chosen in order to avoid common drying artifacts, which occur with most refractory timber-species when subjected to severe drying conditions. This is particularly important in the case of red beech, which is considered to be one of the most refractory timbers of New Zealand.

Replicates were stacked to a height of 500 mm using 20 mm x 20 mm fillets. The distance between stacks was 250 mm. To allow even drying and to avoid "dead" air pockets in the room, the sequence of the boards in each stack was altered and the stacks themselves were shifted round the room to selected positions every second day during the first 7 weeks, and every three days thereafter.

Replicates were weighed every two days during the first 48 days and at three day intervals during the final stages of drying. Despite this very mild schedule some checking occurred. The number of checks and their severity were recorded for each board. After drying (72 days) the final moisture content of each board was again determined using the method described in ASTM D 2016 (1983).

4.6. PRESERVATIVE TREATMENT PROCEEDURES

4.6.1. Board preparation

Each replicate was cross cut into three pieces - two shorter boards and one biscuit from the centre, which was oven dried to estimate the moisture content of the original board. These shortened boards were end sealed with two coats of "Boscrete" and a total of eight replicates for each compression rolling treatment were subsequently treated with CCA salts.

4.6.2. Description of pressure treatment

Each replicate was weighed and subjected to a standard Bethell preservative treatment with a 2.2% aqueous solution of CCA, Treatment followed the new Zealand Timber Preservation Authority (TPA, 1980) commodity specification C 7 using the P4 process, but omitting the final vacuum. The treatment consisted of an initial vacuum of -85 KPa held for 30 min followed by a pressure cycle of 1385 KPa for 2 hrs until refusal was reached. After removal from the pressure cyclinder the samples were allowed to drip dry before a final weighing (the full P4 treatment schedule is accepted for the commercial treatment of the sapwood of red beech).

The boards were then cut in half and a spot-test for the presence of Copper (Chrome - azurol S test, as recommended by the T.P.A.,1980) used to differentiate the preservative penetrated areas in the cross section from unpenetrated areas. Four measurements from the top and four from the bottom surfaces of each board; were taken to determine the average depth of preservative penetration. This method was chosen after establishing that the depth of preservative penetration was uniform enough to be represented by the selected number of measurements. Edge penetration is unaffected by compression rolling (see chapter 7.2.) so edge penetration was not measured.

4.7. MICROSCOPIC EXAMINATIONS

4.7.1. Preparation for light - microscopy

A Stereo microscope (Reichert, Austria) was used to examine areas of damage within a specimen and also to characterize the damage at the macroscopic level; it also proved helpful to differentiating process related damage from preparation artefacts.

Samples were taken at various distances from the surface of the controls and from compression rolled boards and subsequently sectioned into blocks of 5 x 5 x 5 mm. Thin sections (thickness = 15 um) for microscopic slides were prepared using a "OmE" Sledge Microtome (Reichert, Austria). The prepared sections were immersed in distilled water, exposed to a one hour vacuum treatment at -85 kPa, to remove air bubbles from the specimen and subsequently transferred to a microscopic slide, with a drop of glycerine. Glycerine has an appropriate refractive index and is miscible with water. A Nikon Biophot light microscope was used for the observation.

4.7.2. Preparation for scanning electron microscopy (SEM)

Blocks similar to those used in light-microscopic examination were prepared for SEM observation, applying a modified cutting method as described by Exley, Meylan & Butterfield (1977). This consisted of fixing a small specimen in a small vice, and viewing subsequent cutting of the specimen under a Stereo-microscope. This allowed more control over the sliding motion and the cutting angle of the razor blade, since both hands were free to move the cutting tool. Preparation artifacts are to a great extent dependent on the quality of the razor blade and the most satisfactory results were achieved with a GEM model; each blade was only used for two or three cuts, to guarantee a smooth surface. Commonly two planes of each specimen were prepared before it was fixed on a SEM-stub with a conductive copper paint (G.C. Electronics) and subsequently coated with a 50 nanometer layer of gold dust in a Polaron E5000 sputterer, while under to 0.1 Torr vacuum for 5 minutes. Most observations were done on a Cambridge 250 Mark 2 scanning electron microscope, while for the initial observations a Cambridge 400 model was used.

CHAPTER 5: DATA EVALUATION AND ANALYSIS OF RESULTS

5.1. INTRODUCTION

Two computer systems, a PRIME IDR 4130 and a BURROUGHS BG900 in the Computer Center of the University of Canterbury were used for data storage and processing. Most calculations were performed on the PRIME utilising the CHEF - editor (MacLean and Peck, 1982) and then stored on disk. Information to be processed was fed in either by cards or directly through a terminal.

Statistical techniques for data evaluation were used on both systems. Linear regression analysis was carried out on the PRIME with an updated version of the SPSS package (Statistical Package for Social Sciences, Nie et all, 1975; Hull & Nie, 1981), whereas the TEDDYBEAR package was used in conjunction with the BURROUGHS (University of Otago, New Zealand, 1979). TEDDYBEAR statistics package was preferred because of its greater flexibility and its more comprehensive analysis of the data; differences in variability of data within treatments could be detected and reprocessed after an adequate transformation (Steel and Torrie, 1980).

Processing of raw data and all necessary calculations were in FORTRAN, (exclusively run on the PRIME computer), using programmes written and edited by the author. The word processor RUNOFF (Dern, 1980) was used to edit the text files on the PRIME -

computer. The graphs were set up with the Plot 79 programme available on the Burroughs computer (Beebe, 1984).

5.2. METHODS OF ASSESSMENT

5.2.1. Drying rate

The rate of drying of rolled, hot soaked rolled, hot soaked and control boards was determined as described in chapter 4.5. The data was analysed as follows: the dependent variable, drying rate, was obtained from the drying experiment (indicator for diffusivity). A relationship between moisture content and time was established and an equation fitted (Freese, 1967), which described the drying curve above fibre saturation point very accurately:

$$Y = A \times C^{X}, \qquad \text{(Equation 5.1.)}$$

where A and C are constants, Y represents percentage moisture in % and X represents the drying time in days . The linear regression analysis was performed after a semi-logarithmic transformation to:

$LN\ Y = A' + C' \times X$, (Equation 5.2.)

where $A' = LN\ A$ and $C' = LN\ C$

(A corresponds to the original moisture content in %)

Retransformation of regression estimates to arithmetic units can be done as follows:

$$Y = e^{A'} \times (e^{C'})^{X}$$ (Equation 5.3.)

Regression analysis for the drying of each individual board was undertaken separately. Consistently high F - values and R - Square values, never below 0.99, indicated that the transformation did not distort the original values to a significant extent (R - Square values are a measure of the proportion of variance in one variable explained by the other).

The constant C' characterises the transformed drying slope very precisely, hence it was selected as the first dependent variable for the subsequent analysis of variance (Graph 5.1).

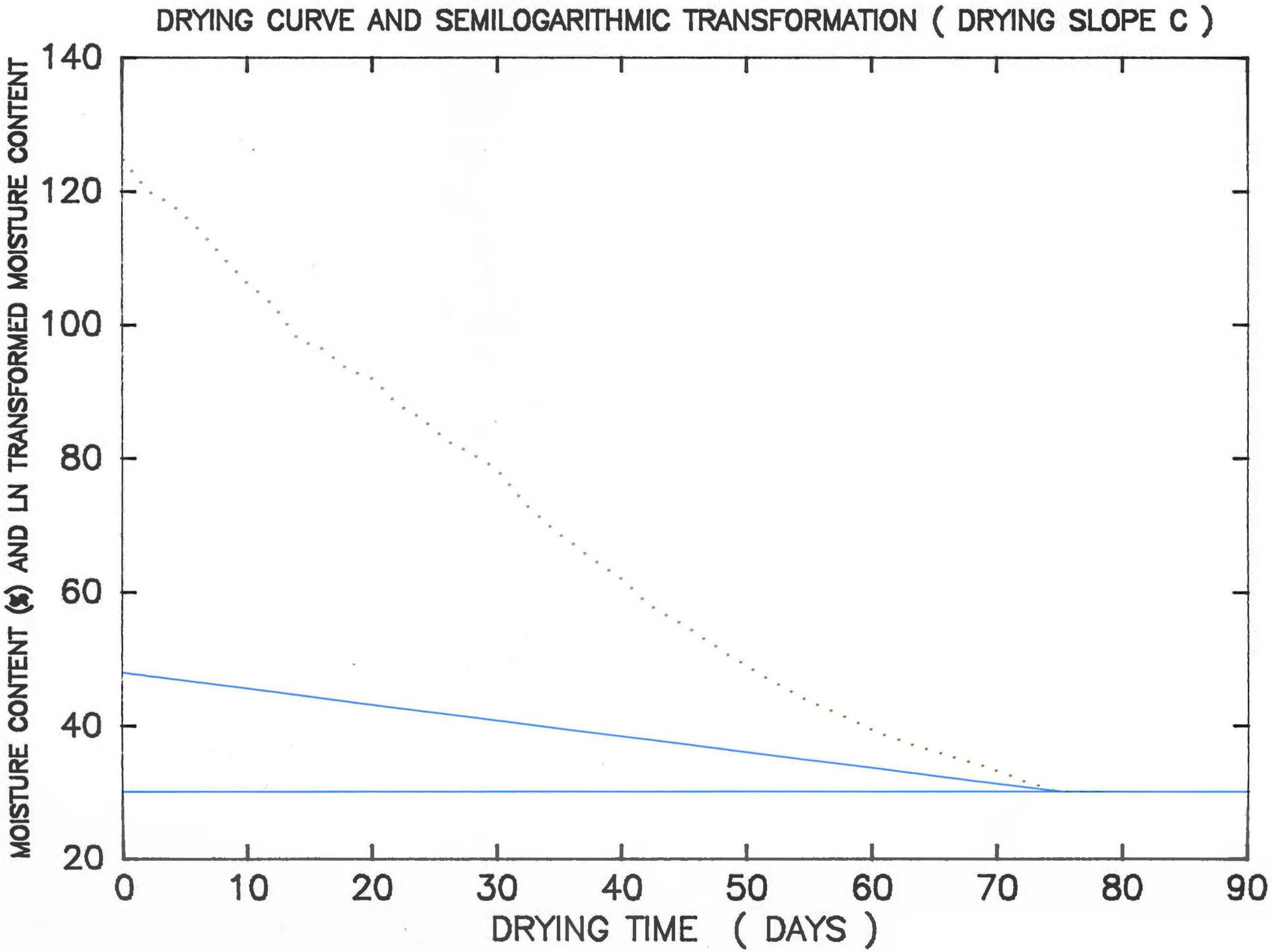
Graph 5.1 Drying curve and semilogarithmic transformation

(Drying slope C')

Green dotted line: Untransformed drying curve (Moisture content/time)

Blue inclined line: LN transformed drying curve (LN of moisture content/ time)

C' represents the slope of the LN transformed drying curve (unit: LN M.C. % / week)


DRYING CURVE AND SEMILOGARITHMIC TRANSFORMATION (DRYING SLOPE C)
MOISTURE CONTENT (%) AND LN TRANSFORMED MOISTURE CONTENT
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
DRYING TIME (DAYS)

5.2.2. Preservative uptake

The dependent variable, preservative uptake (indicator for changes in permeability), was recorded from the pressure impregnation with preservative. The preservative uptake after the treatment process was used as dependent variable and the values represented as a percentage weight increase with respect to the original weight:

$$U = ((W2 - W1)/W1) \times 100\% \qquad \text{(Equation 5.4.)}$$

U being Uptake in percent, W1 weight prior to treatment and W2 weight after treatment in gramm.

5.2.3. Preservative penetration

The variable, preservative penetration (a further indicator for changes in permeability) was obtained from a mean of 8 measurements of depth of preservative penetration per replicate. Only the penetration of the top and bottom faces of the board was considered and measured in mm.

5.3. STATISTICAL ANALYSIS

A multifactorial experiment was set up as a randomized block design with full replication of all treatments. This had the advantage in subsequent analysis of variance that each treatment factor replicated every other factor and therefore extended the range of inference for each factor.

The procedure of ANOVA on the TEDDYBEAR statistical package calculates mean values for different treatments, establishes the significance of individual treatment factors on the respective dependent variable, tests the interaction and/or additive effects of treatments, and tests the variability between treatments with increasing values. Separate analysis of variance were performed:

a) to test the effects of different rolling treatments on diffusivity and permeability
b) to test the effects of grain orientation in unrolled and unsoaked controls on diffusivity and permeability
c) to test the effects of a hot water soaking pretreatment in unrolled controls on diffusivity and permeability with respect to the two grain orientations
d) to test the effect of a combination of hot water soaking pretreatment and compression rolling treatment on diffusivity and permeability with respect to the two grain orientations.

All tests were done for the three previously described dependent variables: drying slope, preservative uptake and preservative penetration. Significance levels in this study are represented as follows:

N.S. = $P > 0.050$;

* = $0.050 > P > 0.010$;

** = $0.010 > P > 0.001$;

*** = $0.001 > P$

5.4. SUMMARY OF RESULTS

5.4.1. Controls

5.4.1.1. Drying rate

The grain orientation did not have an influence on the drying rate of the controls (Table 1.100).

5.4.1.2. Preservative uptake

The grain orientation had a significant influence on the preservative uptake in the controls; the quartersawn boards absorbed 7.8% preservative while the uptake of the flatsawn boards was only 6.2% , (Table 1.200).

5.4.1.3. Preservative penetration

The grain orientation had a significant influence on the preservative penetration of the controls; the average depth of penetration in the quartersawn boards was 1.9 mm, while the flatsawn boards were only penetrated to a depth of 1.5 mm (Table 1.300).

5.4.2. Compression rolled boards at high moisture content

In the analysis which follows statistically significant differences in drying rate are demonstrated for most treatment factors but in practice these improvements are relatively small. In the interpretation of the results it should also be remembered that most boards were substantially damaged.

5.4.2.1. Drying rate

1. The main effects of each treatment factor averaged over all levels of the other factors had a significant influence on the drying rate (Table 1.111).

2. All interactions between treatment factors were non significant (Table 1.111).

3. The overall effect of using the small roller diameter was an improvement in drying rate of 20.1% against the mean of unrolled controls, while the larger roller diameter improved the drying rate against the same controls by 27.7% (compare Table 1.112 with Table 1.100).

4. A relationship between the compression level and drying rate is noticable ; while the 7% compression level improved the drying rate by 14.2% , the 10% level improved it by 23.7% and finally the 13% level accelerated the rate of drying by 28.7% as compared with the controls, (compare Table 1.112, Table 1.100 and Graph 5.4).

5. All rolling treatments improved the drying rate of the flatsawn boards more significantly than the drying rate of the quartersawn boards. The overall improvement for the rolled flatsawn samples was 33.3% against flatsawn

controls, while the improvement for the rolled quartersawn boards against quartersawn controls was 11.7% , (compare Table 1.112 with Table 1.100).

6. The combination of large roller diameter and the 13% compression level applied to the flatsawn and quartersawn boards lead to an improvement in drying rate of 45.2% and 27.8% respectively (compare Table 1.113 with Table 1.100).

5.4.2.2. Preservative uptake

1. Each treatment factor, averaged over all levels of the other factors, had a significant influence on preservative uptake (Table 1.211).

2. The two-way interaction compression level : grain orientation had a significant influence on preservative uptake. The two-way interactions roller diameter : compression level, roller diameter : grain orientation and the three-way interaction roller diameter : compression level : grain orientation, as well as the block effect (inherent variability) were non significant (Table 1.211).

3. Overall the effect of the small roller diameter was to improve preservative uptake against controls by 257% (from 7.0% to a total uptake of 25.0% , weight/weight basis according to equation 6.4) while the large roller diameter increased overall preservative uptake by 339%

(to a total uptake of 31.0% ; compare Tables 1.212 and 1.200).

4. A relationship between compression level and improvement in preservative uptake is noticeable; overall the 7% compression level improved the preservative uptake against controls by 200% (to 21.0%), the 10% level improved it by 297% (to 27.8%) and the 13% compression level increased the uptake by 461 % (to 34.8% ; compare Tables 1.212, 1.200 and Graph 5.2).

5. The overall effect of grain orientation was an improvement in preservative uptake after compression rolling of 331% (to 26.6%) in the flatsawn boards, while the uptake in the quartersawn increased by 273% (to 29.56% compare Tables 1.212 and 1.200).

6. The combination of the large roller diameter and the 13% compression level applied to the quartersawn boards, led to an improvement in preservative uptake by 396% (to 38.7%; compare Tables 1.213 and 1.200).

7. The combination of the large roller diameter and the 13% compression level applied to the flatsawn boards lead to an improvement in preservative uptake by 509% (to 37.6% ; compare Tables 1.213 and 1.200).

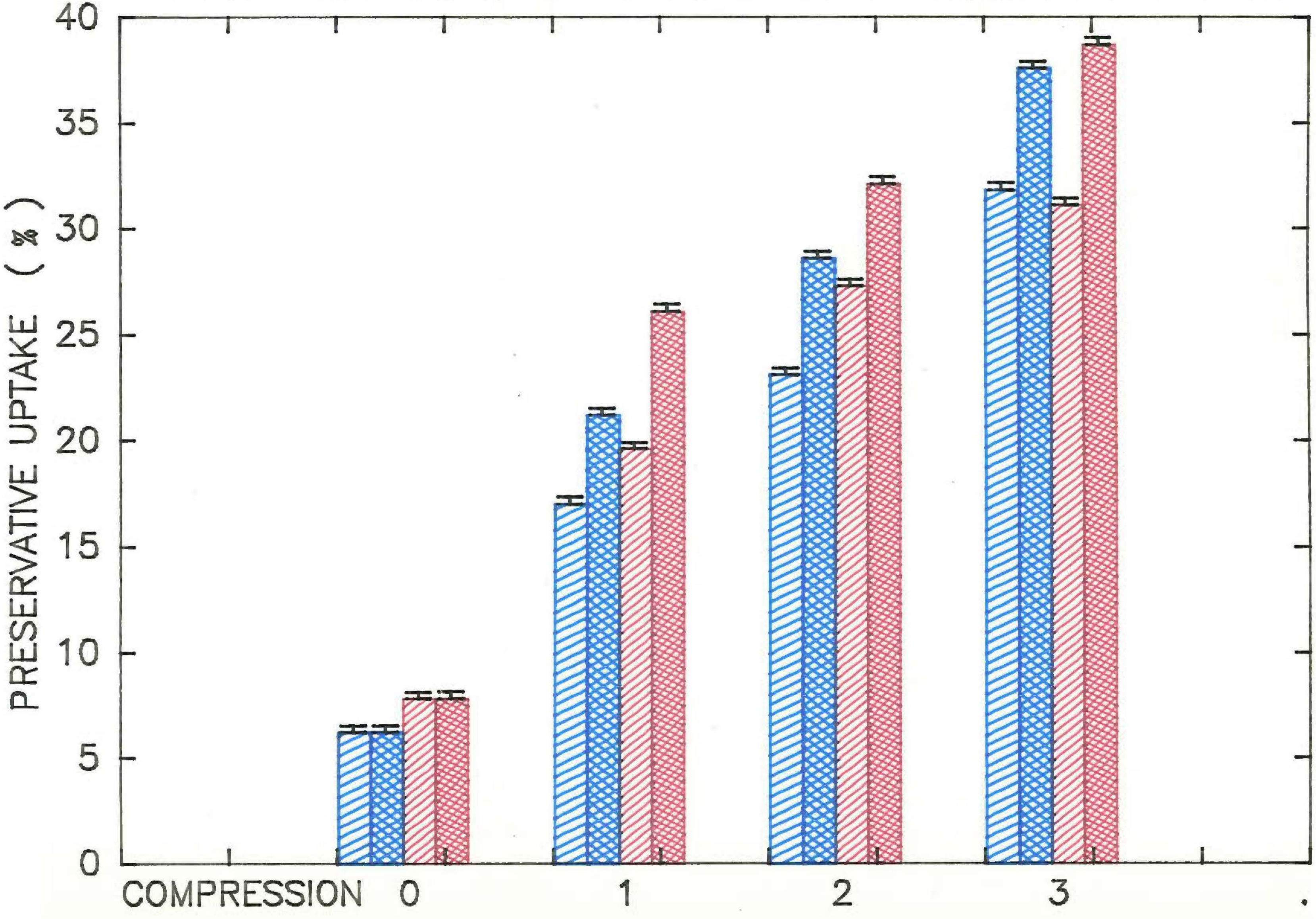
Graph 5.2 Effects of grain orientation and roller size on permeability of N. fusca

Blue: Flatsawn boards
Red : Quartersawn boards
////: Small roller size (50.6 mm diameter)
XXXX: Large roller size (206.8 mm diameter)

Compression level: 0 = Controls
1 = 7 %
2 = 10 %
3 = 13 %

T represents the standard error of the mean

EFFECT OF GRAIN ORIENTATION AND ROLLER SIZE ON PERMEABILITY OF N. FUSCA



5.4.2.3. Preservative penetration

1. Each treatment factor, averaged over all levels of the other factors, had a significant influence on preservative penetration (Table 1.311).

2. The two-way interactions roller diameter : compression level and compression level : grain orientation had a significant influence on the preservative penetration. The two-way interaction roller diameter : grain orientation and the three-way interaction roller diameter : compression level and grain orientation as well as the block effect were non significant, (Table 1.311).

3. The overall effect of the small roller diameter was an improvement in preservative penetration in the faces of the boards by 263% against the mean of all controls (from 1.7 mm to 6.3 mm) while the larger roller diameter improved the preservative penetration overall by 333% (from 1.7 mm to 7.54 mm; compare Tables 1.312 and 1.300).

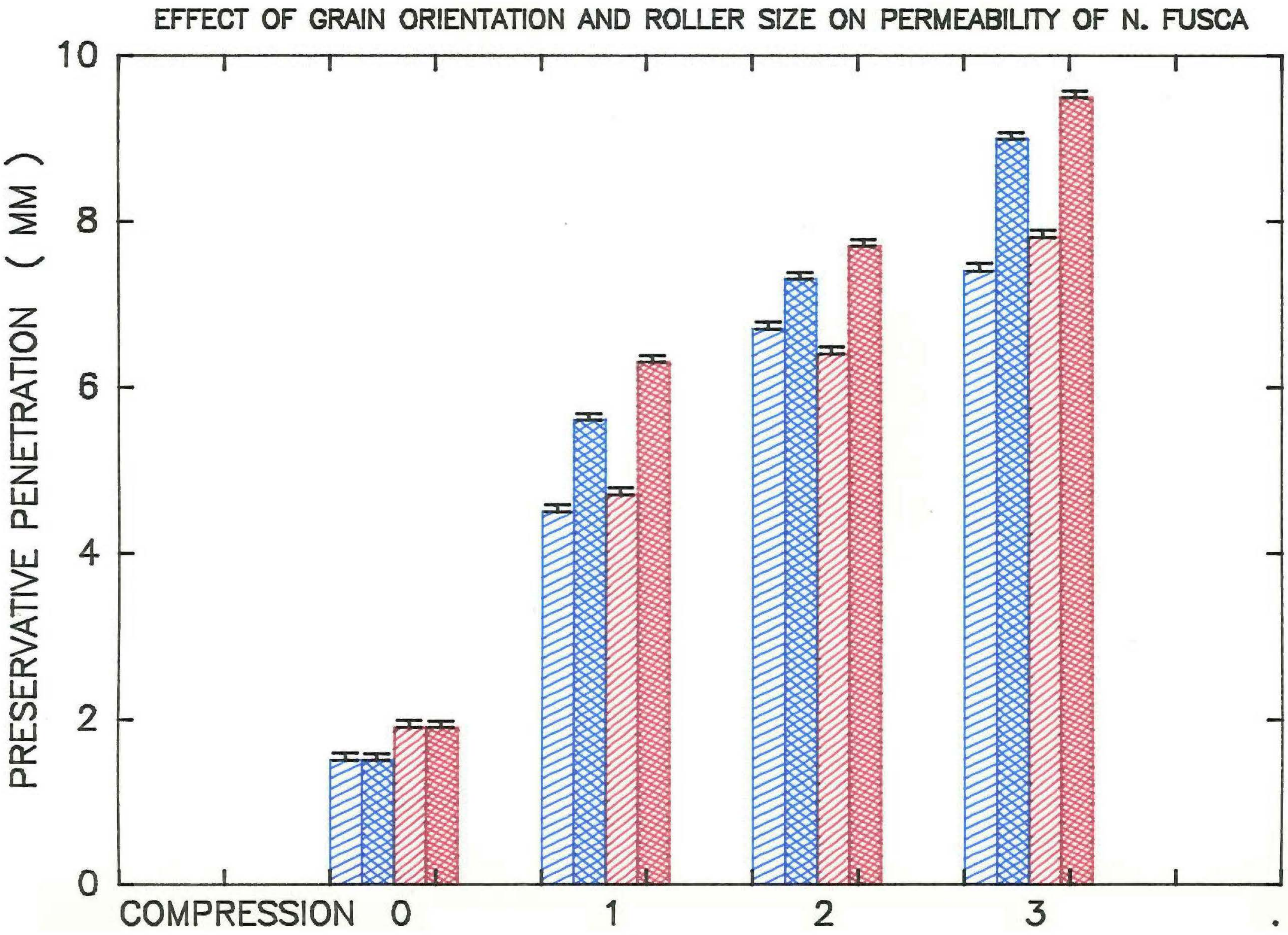
4. A relationship between increasing compression level and overall improvement in preservative penetration is noticible; while the 7% compression level improved the depth of preservative penetration by 205% , (to 5.3 mm), the 10% level improved it by 295% , (to 6.9 mm) and the 13% compression level increased the preservative penetration by 394% , (to 8.6 mm; compare Tables 1.312, 1.300 and Graph 5.3).

Graph 5.3 Effects of grain orientation and roller size on permeability of <u>N.fusca</u>

Blue : Flatsawn boards
Red : Quartersawn boards
: Small roller size (50.6 mm diameter)
: Large roller size (206.8 mm diameter)

Compression level: 0 = Controls
1 = 7 %
2 = 10 %
3 = 13 %

represents the standard error of the mean


EFFECT OF GRAIN ORIENTATION AND ROLLER SIZE ON PERMEABILITY OF N. FUSCA
PRESERVATIVE PENETRATION (MM)
10
8
6
4
2
0
COMPRESSION 0
1
2
3

5. The overall effect of grain orientation was an improvement in preservative penetration for the flatsawn boards by 331% , (from 1.5 mm to 6.6 mm), while penetration for the quartersawn increased by 272% , (from 1.9 mm to 7.2 mm; compare Tables 1.312 and 1.300).

6. The combination of the large roller diameter and the 13% compression level applied to the quartersawn boards, lead to an improvement in preservative penetration by 391% (from 1.9 mm to 9.5 mm; compare Tables 1.313 and 1.300).

7. The combination of the large roller diameter and the 13% compression level applied to the flatsawn boards lead to an improvement in preservative penetration to 508% (from 1.5 mm to 9.4 mm; compare Tables 1.313 and 1.300).

5.4.3. Hot-water soaked controls and unsoaked controls

5.4.3.1. Drying rate

1. The two treatment factors, pretreatment and grain orientation, individually had a significant overall influence on the drying rate (Table 1.411).

2. The two-way interaction, pretreatment : grain orientation, also had a significant effect on the drying rate (Table 1.411).

3. The overall effect of the hot soak pretreatment against non- pretreated controls was an improvement in drying rate

of 87% , (Table 1.411)

4. The comparison of hot soaked, quartersawn boards with non hot soaked quartersawn controls showed an improvement in drying rate for the hot soaked boards by 73.1%. The hot soak pretreatment had an even more pronounced effect on the flatsawn boards, improving the drying rate against flatsawn controls by 101.2% (Table 1.412 and Graph 5.4).

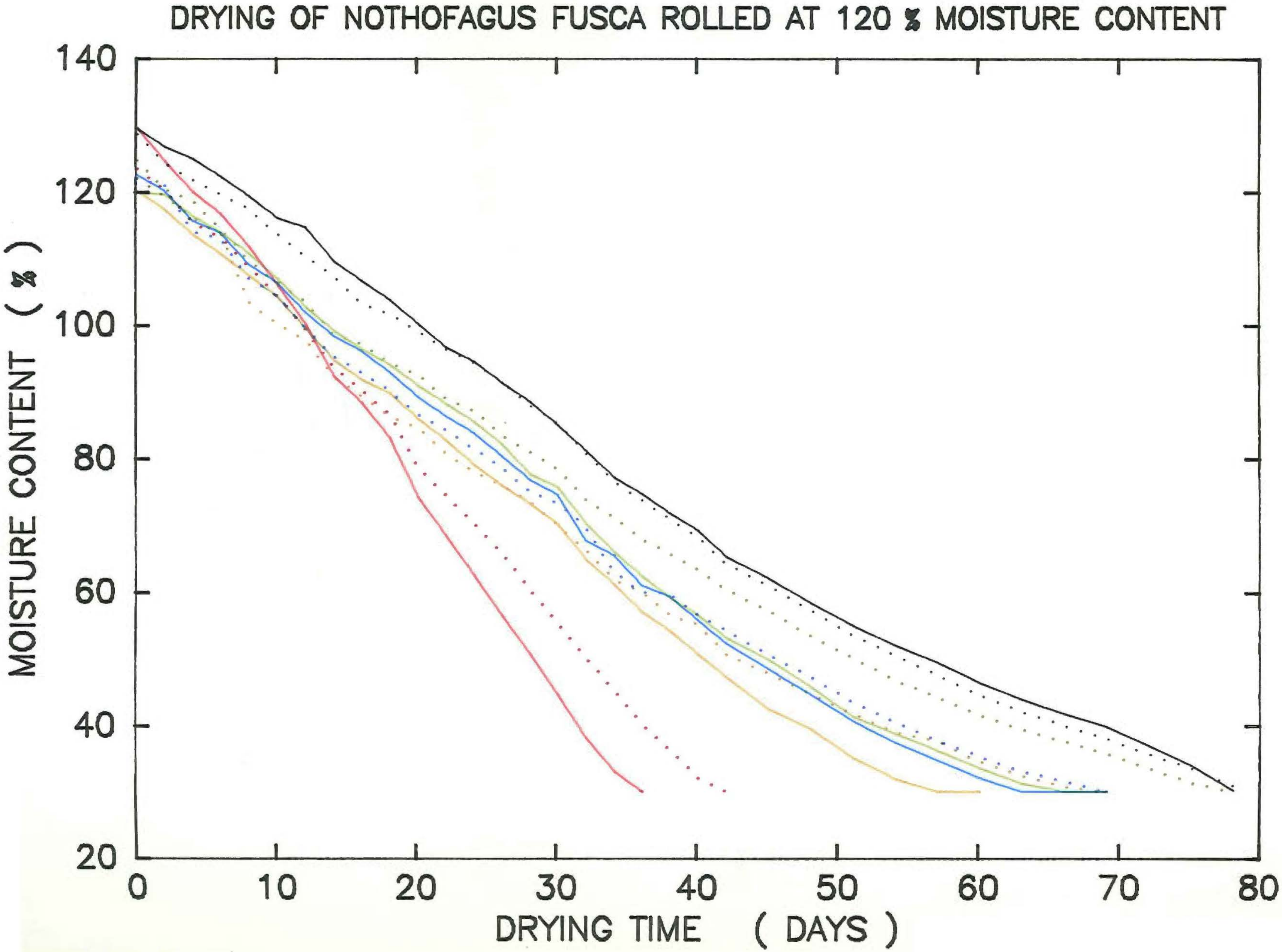
Graph 5.4 Drying of <u>Nothofagus fusca</u> rolled at 120% moisture content

(Each line represents the mean of four replicates)

Continuous lines: Flatsawn boards
Dotted lines: Quartersawn boards

Black:	Controls
Red:	Hot water soaked controls
Green:	7% compression level
Blue:	10% compression level
Gold:	13% compression level

Rolling conditions; Feed speed: 1000 mm/s
Roller size: 206.8 mm


DRYING OF NOTHOFAGUS FUSCA ROLLED AT 120 % MOISTURE CONTENT
MOISTURE CONTENT (%)
DRYING TIME (DAYS)
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80

5.4.3.2. Preservative uptake

1. The individual treatment factors, hot soak pretreatment and grain orientation, had no significant overall influence on the preservative uptake (Table 1.511).

2. The two-way interaction, hot soak pretreatment : grain orientation, did not have a significant effect on the preservative uptake (Table 1.511).

3. The hot soak pretreatment improved preservative uptake to a minor extent from 7.4% to 8.0% , on a weight to weight basis according to equation 6.4, (Table 1.511).

4. Quartersawn boards showed greater preservative uptake of 8.5% preservative adsorbed against 7.0% for flatsawn boards, on a weight to weight basis (Table 1.512).

5. The comparison of hot soak pretreated, quartersawn boards with non-pretreated quartersawn controls showed an improvement in preservative uptake for the pretreated boards from 7.7% to 9.3% , on a weight to weight basis while the pretreatment had no effect on the flatsawn boards (Table 1.512).

5.4.3.3. Preservative penetration

1. The individual treatment factors, hot soak pretreatment and grain orientation, individually had no significant overall influence on the preservative penetration (Table

1.611).

2. The two-way interaction, hot soak pretreatment : grain orientation, did not have a significant effect on the preservative penetration (Table 1.611).

3. The hot soak pretreatment improved preservative penetration to a minor extent from 1.87 mm to 2.08 mm (Table 1.611).

4. The overall effect of grain orientation was statistically significant. Preservative penetration in the quartersawn boards was on average 1.46 mm, while the flatsawn boards showed a slightly lower mean penetration value of 1.38 mm (Table 1.612).

5. The comparison of hot soak pretreated, quartersawn boards with non-pretreated quartersawn controls showed an improvement in preservative penetration for the pretreated boards from 1.38 mm to 1.53 mm, while the pretreatment had no effect on the flatsawn boards (Table 1.612).

5.4.4. Hot-water soaked and compression rolled boards

As with the unsoaked, compression rolled boards, substantial damage was present in the hot-soaked boards after the rolling treatment. This has to be considered during the interpretation of the following statistical analysis.

5.4.4.1. Drying rate

1. The treatment factors, pretreatment and grain orientation, individually had significant influence on the drying rate, while the compression level had no significant effect (Table 1.711).

2. The interaction between pretreatment : compression level and and compression level : grain orientation also had a significant effect on the drying rate (Table 1.711).

3. The overall improvement in the drying rate of hot-water soaked, rolled against unsoaked rolled boards was 51.7% (Table 1.712).

4. None of the compression levels had a significant effect on the drying rate (Table 1.712).

5. Overall a slight difference in drying rate between quartersawn and flatsawn boards was noticed, the latter drying about 9.5% faster, although the variance-ratio test detected a significant ratio in error variance between treatments (Table 1.712).

6. The combination of a hot soak pretreatment, 7% compression level (rolling at medium feed-speed with large rollers) applied to the flatsawn boards improved their drying rate against non pretreated flatsawn boards, compression rolled at the same conditions by 68.5% (Table 1.713).

7. The combination of a hot soak pretreatment, 7% compression level (rolling at medium feed-speed with large rollers) applied to the quartersawn boards improved their drying rate against non pretreated quartersawn boards, compression rolled at the same conditions by 77.7% (Table 1.713).

5.4.4.2. Preservative uptake

1. The individual treatment factors, hot soak, compression level and grain orientation, had significant influence on the preservative uptake (Table 1.811).

2. The two-way interaction compression level : grain orientation and the three-way interaction hot soak : compression level : grain orientation had significant influence on the preservative uptake (Table 1.811).

3. The overall effect of the hot-water pretreatment was significant between hot soaked:rolled and unsoaked:rolled boards; the former absorbing 175% more preservative than unrolled and unsoaked controls (from 7.0% to 19.2% uptake on a weight to weight basis according to equation 6.4) while the uptake in the latter was improved by 342% to 30.9% on a weight to weight basis; compare Tables 1.812 and 1.200).

4. A relationship between increase in compression level

and improvement in preservative uptake can be seen; overall the 7% compression level improved the preservative uptake against unrolled and unsoaked controls by 164.1% (from 7.0% to 18.5% on a weight to weight basis according to equation 5.4), the 10% level improved it by 248.6% , (to 24.4% on a weight to weight basis), and finally the 13% level increased the uptake by 361.1% (to 32.3% on a weight to weight basis; compare Tables 1.812 and 1.200)

5. Overall a difference in preservative uptake between , hot water soaked and rolled flatsawn and quartersawn boards was noticible; the mean uptake for the flatsawn boards was improved against unsoaked and unrolled controls by 284.1% (from 6.2% to 23.7% on a weight to weight basis), whereas the quartersawn boards absorbed 238.5% more treatment solution than the corresponding quartersawn controls (from 7.8% to 26.41% on a weight to weight basis; compare Tables 1.812 and 1.200).

6. The combination of the hot soak pretreatment with compression rolling at the 13% compression level (rolling at medium speed with the large roller) applied to the flatsawn boards improved their preservative uptake against unsoaked, unrolled flatsawn boards by 305.2% whilest the flatsawn boards compression rolled at 13% compression level but without the hot soak pretreatment improved their preservative uptake against unsoaked, unrolled flatsawn

controls by 522.4%. Thus the average % uptake (on a weight to weight basis) of the heat treated, rolled boards was 25.02%, that of the not heated, rolled boards was 38.4% and that of the controls was 6.2% (Compare Tables 1.813 and 1.200).

7. The combination of the hot soak pretreatment with compression rolling at the 13% compression level (rolling at medium speed with the large roller) applied to the quartersawn boards improved their preservative uptake against unsoaked, unrolled quartersawn boards by 275.6% whilest the quartersawn boards compression rolled at 13% compression level but without the hot soak pretreatment improved their preservative uptake against unsoaked, unrolled flatsawn controls by 368.6%. Thus the average % uptake (on a weight to weight basis) of the heat treated, rolled boards was 29.3%, that of the not heat treated, rolled boards was 36.6% and that of the controls was 7.8% (Compare Tables 1.813 and 1.200).

5.4.4.3. Preservative penetration

1. The individual treatment factors, hot soak, compression level and grain orientation, had significant influence on preservative penetration (Table 1.911).

2. The two-way interaction compression level : grain orientation and the three-way interaction hot soak : compression level : grain orientation had significant

influence on preservative penetration (Table 1.911).

3. The overall effect of the hot-water pretreatment was significant between hot soaked:rolled and unsoaked:rolled boards; the latter showing an average preservative penetration of 7.6 mm, while the former were penetrated to a mean depth of 4.8 mm (against 1.7 mm mean depth of penetration in unsoaked and unrolled controls; compare Tables 1.912 and 1.300).

4. A relationship between increase of the compression level and overall improvement in preservative penetration can be noticed; the 7% compression level improved the preservative penetration from 1.7 mm in unsoaked and unrolled controls to 4.5 mm, 10% level improved it to 6.0 mm and finally the 13% compression level increased it to 8.0 mm, (compare Tables 1.912 and 1.300).

5. Overall a difference in preservative penetration between the flatsawn and quartersawn boards was noticible; the mean penetration in flatsawn boards was 5.8 mm, whereas the depth of penetration in the quartersawn boards reached average levels of 6.5 mm (compared with 1.5 mm and 1.9 mm in the respective unsoaked and unrolled controls; Tables 1.912 and 1.300).

6. The combination of the hot soak pretreatment with compression rolling at the 13% compression level (rolling at medium speed with the large roller) applied to the

flatsawn boards improved their preservative peneti against unsoaked, unrolled flatsawn boards by 306.7% whilest the flatsawn boards compression rolled at 13% compression level but without the hot soak pretreatment improved their preservative penetration against unsoaked, unrolled flatsawn controls by 533.3%. Thus the average penetration of preservatives in the heat treated, rolled boards was 6.1 mm, that of the not heat treated, rolled boards was 9.5 mm and that of the controls was 1.5 mm (Compare Tables 1.913 and 1.300).

7. The combination of the hot soak pretreatment with compression rolling at the 13% compression level (rolling at medium speed with the large roller) applied to the quartersawn boards improved their preservative penetration against unsoaked, unrolled quartersawn boards by 284.4% whilest the quartersawn boards compression rolled at 13% compression level but without the hot soak pretreatment improved their preservative penetration against unsoaked, unrolled flatsawn controls by 373.7%. Thus the average penetration of preservatives in the heat treated, rolled boards was 7.3 mm, in the not heat treated, rolled boards it was 9.0 mm and that of the controls was 1.9 mm (Compare Tables 1.913, 1.300 and Graph 5.5).

Graph 5.5 Effects of rolling and hot soak on permeability of N.fusca

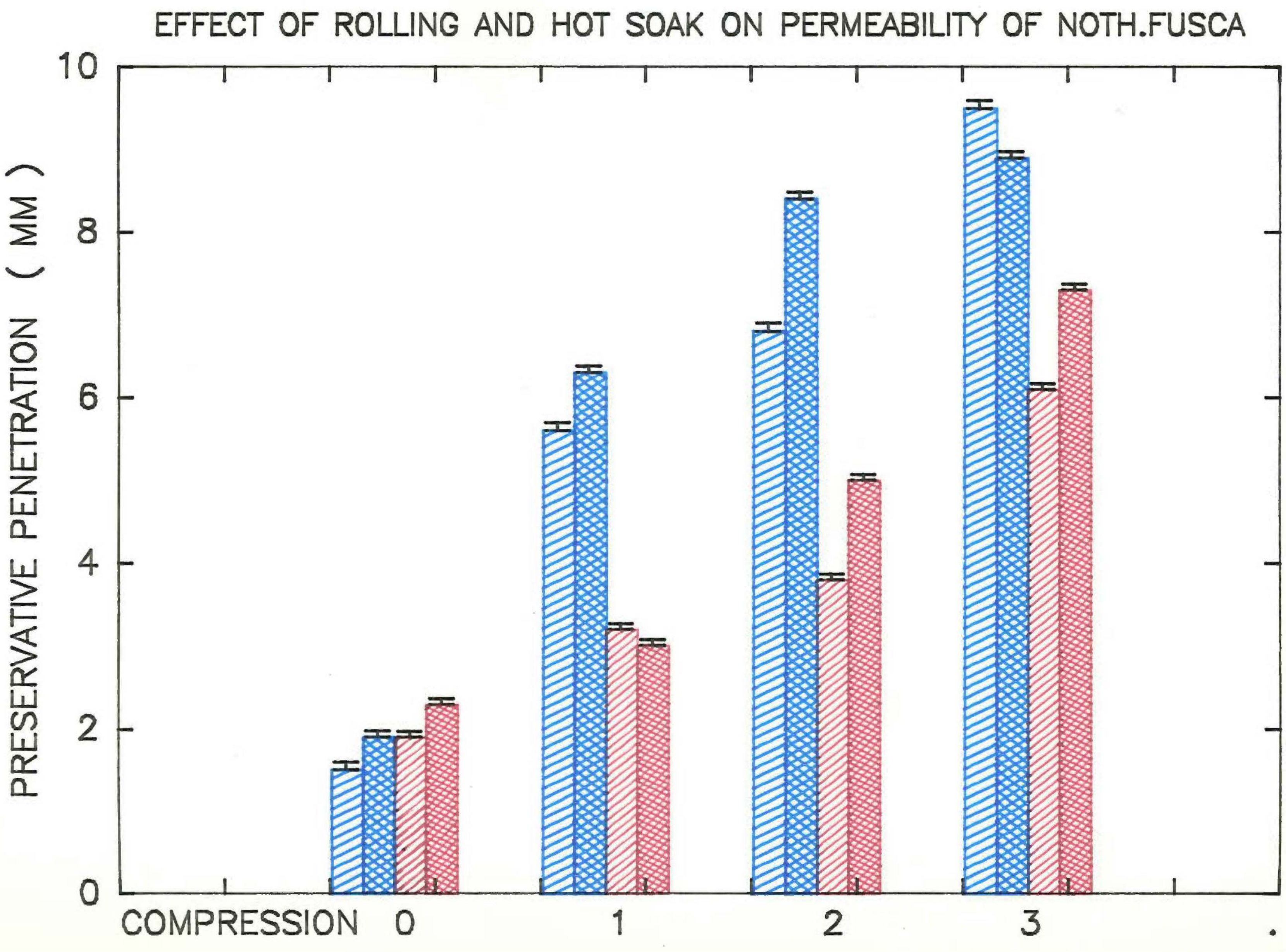
(Each bar represents the mean penetration of 8 replicates)

Blue : Unsoaked boards
Red : Hot water spaked boards
////// : Flatsawn boards
XXXX : Quartersawn boards

Compression level: 0 = Controls
1 = 7 %
2 = 10 %
3 = 13 %

T represents the standard error of the means

Rolling conditions; Roller size: 206.8 mm
Feed speed : 1000 mm/s


EFFECT OF ROLLING AND HOT SOAK ON PERMEABILITY OF NOTH.FUSCA
PRESERVATIVE PENETRATION (MM)
0
2
4
6
8
10
COMPRESSION 0
1
2
3

5.4.5. Effects of the treatment factor feed speed on preservative uptake of boards rolled at 60% moisture content

These results correspond to experiments with boards from a different log of *Nothofagus fusca* (chapter 4.3.1.). There was no macroscopic evidence of damage in the boards at any of the tested feed speeds. However there was significant error variance (E.V.) between the results of the two treatments, which was due to variation in feed speed during rolling.

1. The effect of feed speed was highly significant (Table 3.111).
2. The effect of grain orientation was highly significant (Table 3.111).
3. Compression rolling at all four feed speeds improved preservative uptake in quartersawn boards more than in the flatsawn boards, average preservative uptake overall in the former was increased by 336.4% against quartersawn controls (20.5% total uptake against 4.7% on a weight to weight basis), while in the latter uptake was only increased by 230% against flatsawn controls (26.1% total uptake against 7.9% on a weight to weight basis, see Table 3.112 and Graph 5.6).

Graph 5.6 Effects of rolling speed and moisture content on preservative uptake of <u>N. fusca</u>

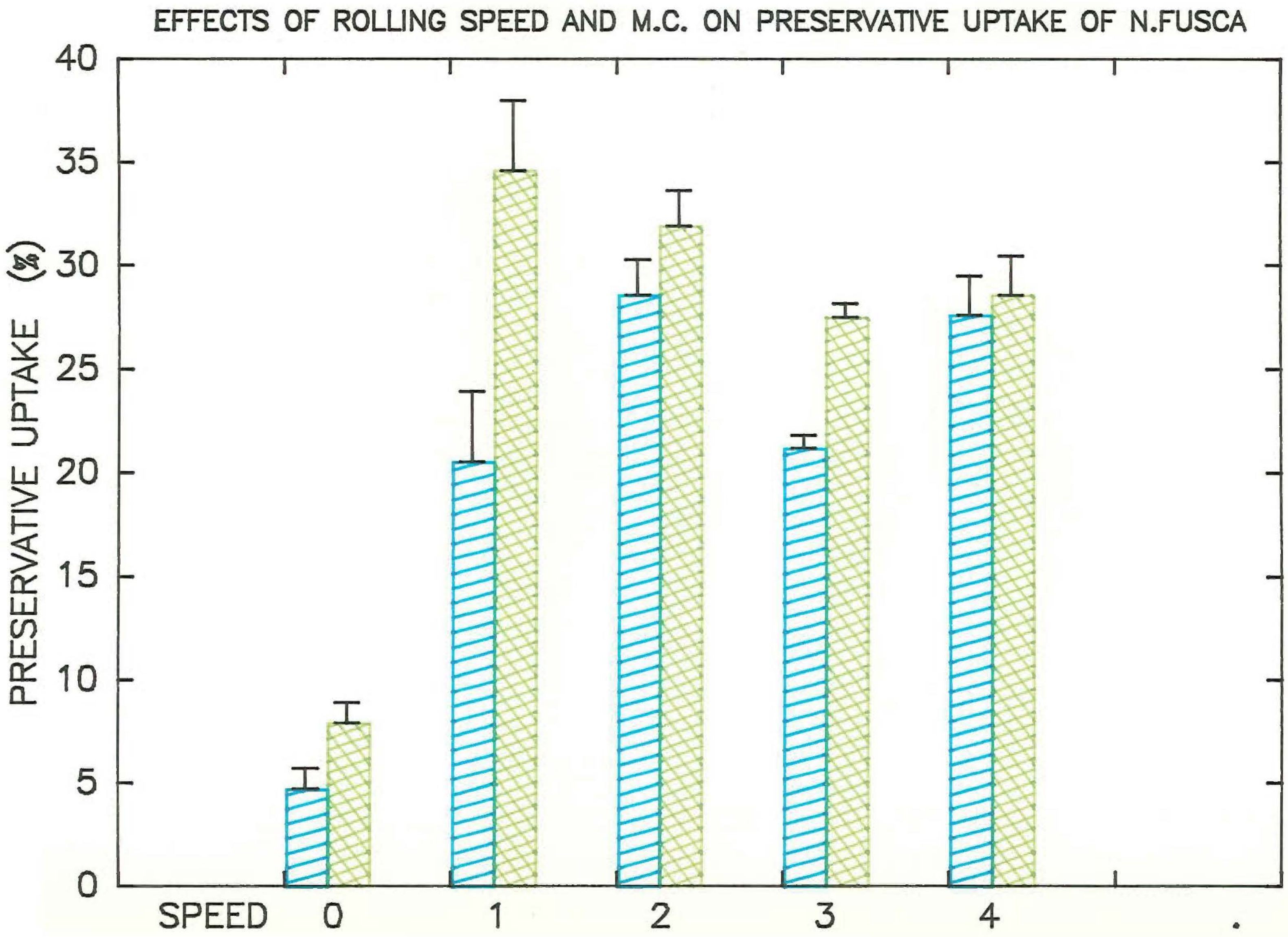
(Each bar represents the mean uptake of 4 replicates)

Blue: Flatsawn boards
Green: Quartersawn boards

Speed: 0 = Controls
1 = 500 mm/s (nominal)
2 = 1000 mm/s (nominal)
3 = 2000 mm/s (nominal)
4 = 3000 mm/s (nominal)

represents the standard error of the mean

Rolling conditions; Roller size: 206.8 mm
Compression level : 10 %


EFFECTS OF ROLLING SPEED AND M.C. ON PRESERVATIVE UPTAKE OF N.FUSCA
PRESERVATIVE UPTAKE (%)
0
5
10
15
20
25
30
35
40
SPEED
0
1
2
3
4

4. No beneficial effects in terms of improvement in preservative uptake were achieved by increasing the feed speed. While in the flatsawn boards the highest improvement was recorded at a feed speed of 500 mm/s (34.6% on a weight to weight basis in comparison to 7.9% in flatsawn controls), in the quartersawn boards best results were achieved at 1000 mm/s (28.6% compared with 4.7% in quartersawn controls; see Table 3.112 and Graph 5.6).

5.4.6. Effects of the treatment factor compression level on preservative uptake of boards rolled at 20% moisture content

These results were obtained from a small number of replicates which were chosen from the same logs as the samples selected for the multifactorial experiment (Chapter 4.3.2). No damage of the boards at macroscopical level ocurred with any of the three compressions.

1. The effect of the compression level was highly significant (Table 2.100).

2. At a constant feed speed of 1000 mm/s and using the large roller diameter (206.8 mm) the preservative uptake in flatsawn boards was increased from 10.5% in the controls to 46.2% at the 7% compression level, to 54.3% at the 10% compression level and to 63.9% at the 13% compression level (compared these results with those obtained at corresponding compression levels during

rolling of boards at high moisture contents, namely 21.2%, 28.6% and 37.6% respectively all on a weight to weight basis according to equation 6.4; Tables 2.100, 1.213 and Graph 5.7).

Graph 5.7 Effects of moisture content during rolling on permeability of <u>N. fusca</u>

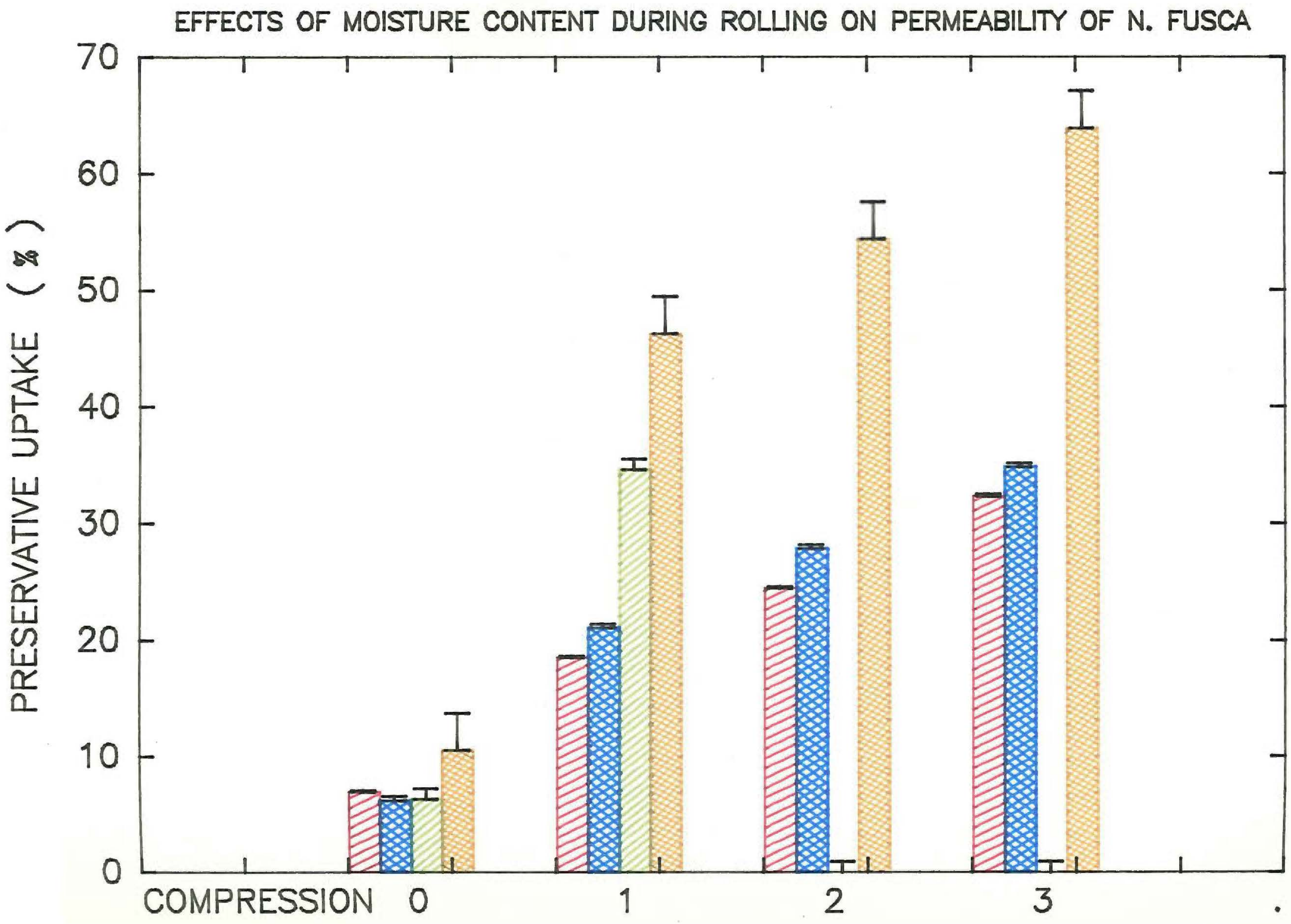
(Each bar represents the mean uptake of 4 replicates)

Red : Quartersawn boards rolled at initial moisture contents around 120 %
Blue : Flatsawn boards rolled at initial moisture contents around 120 %
Green: Flatsawn boards rolled at initial moisture contents around 60 %
Gold : Flatsawn boards rolled at initial moisture contents around 20 %

Compression level: 0 = Controls
1 = 7 %
2 = 10 %
3 = 13 %

⊤ represents the standard error of the mean

Rolling conditions; Roller size = 206.8 mm
Feed speed = 1000 mm/s



EFFECTS OF MOISTURE CONTENT DURING ROLLING ON PERMEABILITY OF N. FUSCA
PRESERVATIVE UPTAKE (%)
70
60
50
40
30
20
10
0
COMPRESSION
0
1
2
3

5.4.7. Effects of the treatment factor feed speed on the strength properties of Nothofagus fusca compression rolled at 60% moisture content

These results correspond to experiments with boards from a different log of Nothofagus fusca (chapter 4.3.1.). The analysis of variance tested the effects of compression rolling on the modulus of rupture (MOR), on the modulus of elasticity and on the total work to failure or toughness (WTF). The results of this analysis are summarized in the following text and in the corresponding tables, however interpretation and discussion of these findings will be done at a later date, since one part of the strength testing programm, the wedge hardness tests, are still in progress. All compression rolling tests in this experiment were done with the large roller size (206.8 mm) and at the 10% compression level.

1. There was a statistically significant effect of feed speed on the MOR at the 94.66% confidence level. The decrease in MOR was recorded at a nominal feed speed of 3000 mm/s (although feed speed did not remain constant during compression rolling of individual boards), reducing the value for flatsawn controls from 115.46 N/mm^2 (controls) to 109.22 N/mm^2 (equivalent to a reduction in MOR by 5.4%). The MOR of the quartersawn boards, compression rolled at the same conditions was reduced from 117.96 N/mm^2 for the unrolled controls to 98.36 N/mm^2 (equivalent to a reduction of the MOR by 16.6%; compare

Tables 3.211, 3.212 and Graph 5.8).

2. There was no statistically significant difference between the effects of compression rolling on the MOR of quartersawn and flatsawn boards (Table 3.212 and Graph 5.8)

3. The individual treatment factors feed speed and grain orientation had significant influence on the MOE (Table 3.311).

4. The MOE of flatsawn boards rolled at 3000 mm/s was reduced from 10643 N/mm^2 for controls to 10042 N/mm^2 (equivalent to a 5.6% reduction of the MOE) whereas the MOE of quartersawn boards rolled at the same conditions was reduced from 10327 N/mm^2 (controls) to 8469 N/mm^2 (equivalent to a 18% reduction of MOE; Tables 3.312 and Graph 5.8).

5. Compression rolling did not influence total work to failure (toughness) significantly in either quartersawn or flatsawn boards at any of the four feed speeds (Tables 3.411, 3.412 and Graph 5.8)

Graph 5.8. Effects of compression rolling on the strength properties of Nothofagus fusca

(Each bar represents the mean of 12 replicates)

Green : Modulus of rupture (MOR)
Blue : Modulus of elasticity (MOE)
Red : Total work to failure, toughness (WTF)

Speed: 0 = Controls
1 = 500 mm/s (nominal)
2 = 1000 mm/s (nominal)
3 = 2000 mm/s (nominal)
4 = 3000 mm/s (nominal)

⊤ represents the standard error of the mean

Rolling conditions; Roller size: 206.8 mm
Compression level : 10 %

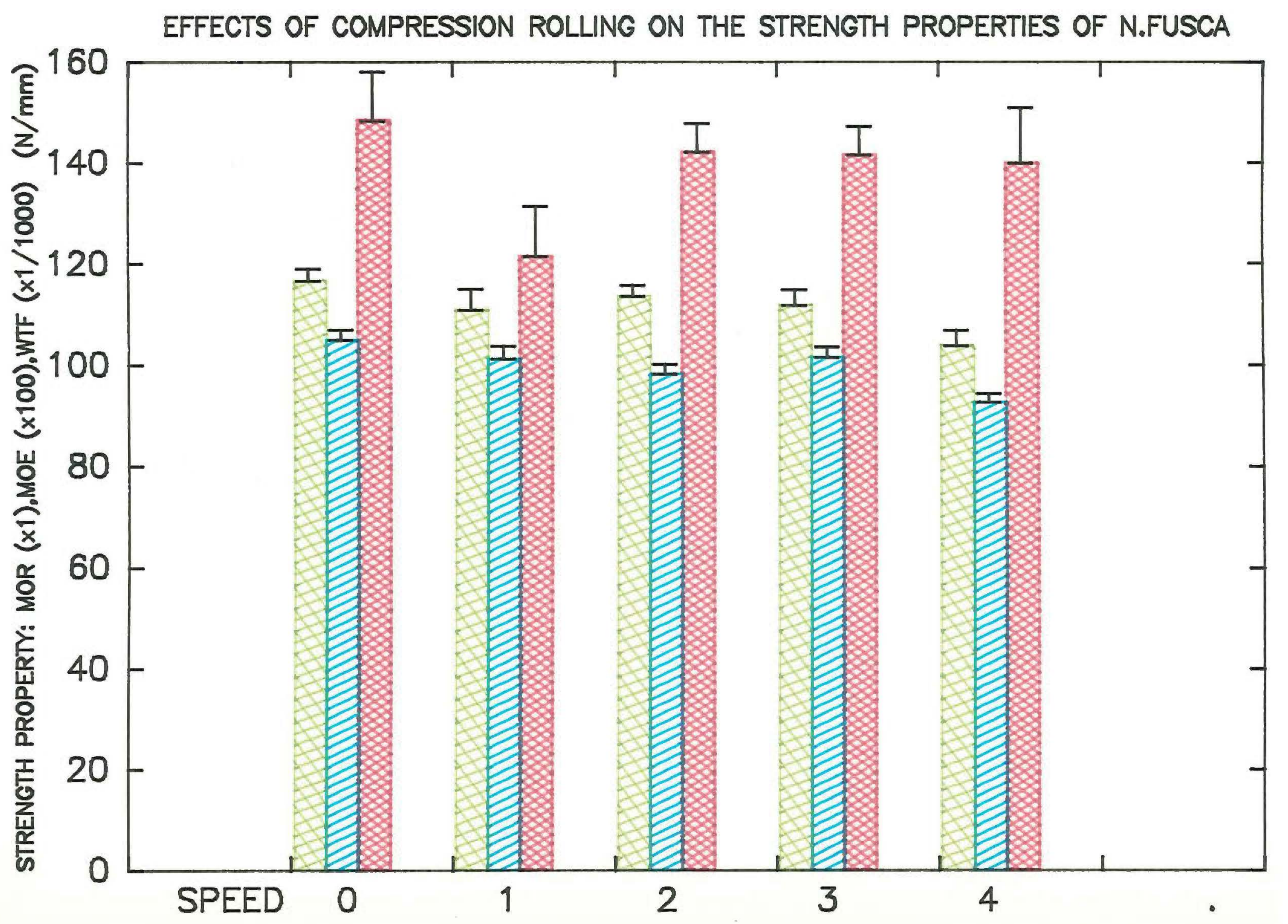

EFFECTS OF COMPRESSION ROLLING ON THE STRENGTH PROPERTIES OF N.FUSCA
STRENGTH PROPERTY: MOR (x1),MOE (x100),WTF (x1/1000) (N/mm)
160
140
120
100
80
60
40
20
0
SPEED
0
1
2
3
4

Table 1.100 :

Summary of ANOVA for testing the effects of grain orientation on the drying characteristics of <u>Nothofagus fusca</u> (controls)

Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (ln m.c./week)
Independent Variable 1: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
GRAIN ORIENT.	0.00016	1	0.00016	0.27675	N.S.
ERROR	0.00180	14	0.00013		
TOTAL	0.00196	15	0.00013		

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E
QUARTERSAWN	-0.1286	0.0110	0.0039
FLATSAWN	-0.1221	0.0115	0.0041
MEAN Q/F	-0.1254		

VARIANCE-RATIO TEST : F = 1.0912; D.F. = 7;7;
P = 0.9113; N.S.
Ratio of E.V. between the two grain orientations is not significant

COEFFICIENT OF VARIATION = 9.04%

Table 1.200 Controls

Summary of ANOVA for testing the effects of grain orientation on the permeability characteristics of <u>Nothofagus fusca</u>

Dependent Variable: PRESERVATIVE UPTAKE IN% (Wt/Wt)
Independent Variable 1: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNI-FICANCE
GRAIN ORIENT.	29.2259	1	29.2259	0.02245	*
ERROR	218.526	42	5.2030		
TOTAL	247.757	43	5.7617		

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTERSAWN	7.80	2.24	0.48
FLATSAWN	6.17	2.31	0.49
MEAN Q/F	7.00		

VARIANCE-RATIO TEST : F = 1.0663; D.F. = 21,21;
P = 0.884440; N.S.

Ratio of E.V. between the two grain orientations is not significant

COEFFICIENT OF VARIATION = 19.42 %

Table 1.300:

Summary of ANOVA for testing the effects of grain orientation on the permeability characteristics of <u>Nothofagus fusca</u>

Dependent Variable: PRESERVATIVE PENETRATION IN MM
Independent Variable 1: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
GRAIN ORIENT.	1.71628	1	1.71628	0.02510	*
ERROR	13.3595	42	0.31808		
TOTAL	15.0758	43	0.35060		

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTERSAWN	1.94	0.55	0.12
FLATSAWN	1.54	0.57	0.12
MEAN Q/F	1.74		

VARIANCE-RATIO TEST : F = 1.0646; D.F. = 21,21;
P = 0.887314; N.S. *

Ratio of E.V. between the two grain orientations is not significant

COEFFICIENT OF VARIATION = 20.37%

Table 1.111

Summary of ANOVA for testing the effects of three different treatment factors on the drying of Nothofagus fusca, compression rolled at high moisture content

Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C'
Independent Variable 1: ROLLER DIAMETER (DIAMETER)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
DIAMETER	0.00105	1	0.00105	0.04317	*
COMPR.	0.00806	2	0.00403	0.00001	***
GR.OR.	0.01309	1	0.01309	0.00000	***
TWO-WAY INTERACTIONS					
DIAMETER and COMPR.	0.00191	2	0.00096	0.02534	*
DIAMETER and GR.OR.	0.00001	1	0.00001	0.86370	N.S.
COMPR. and GR.OR.	0.00005	2	0.00003	0.90355	N.S.
THREE-WAY INTERACTION					
DIAMETER COMPR. and GR.OR.	0.00059	2	0.00029	0.31504	N.S.
R	0.02684	11	0.00024	0.48064	N.S.
ERROR	0.03055	121	0.00025		
TOTAL	0.05799	143	0.00041		

Table 1.112: Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (continue)

FACTOR: ROLLER DIAMETER (SMALL= 50.6MM; BIG= 206.8MM)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
SMALL	-0.1505	0.0177	0.0021
BIG	-0.1559	0.0137	0.0016

F = 1.6716; D.F.= 61,61; P = 0.046867 ; RATIO E.V.: *

FACTOR: COMPRESSION (%)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	-0.1432	0.0173	0.0025
10%	-0.1550	0.0152	0.0022
13%	-0.1613	0.0151	0.0022

BARTLETT'S TEST M/C = 0.9682; P = 0.616244 ; N.S.

FACTOR: GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	-0.1436	0.0146	0.0017
(CONTROL	-0.1286)		
FLAT	-0.1627	0.0171	0.0020
(CONTROL	-0.1221)		

VARIANCE-RATIO TEST: F= 1.3706; D.F.= 61,61,
P= 0.2211; N.S.

Table 1.113: (continue)

MEANS

REGRESSION ADJUSTED DRYING SLOPE C'(LN M.C. / WEEK)

ROLLER DIAMETER	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
(CONTROLS		-0.129	-0.122)
SMALL	7%	-0.132	-0.154
	10%	-0.145	-0.165
	13%	-0.147	-0.160
BIG	7%	-0.134	-0.152
	10%	-0.148	-0.163
	13%	-0.156	-0.182

GRAND MEAN = -0.153; COEFFICIENT OF VARIATION = 10.37%

Table 1.211:

Summary of ANOVA for testing the effects of three different treatment factors on the permeability characteristics of Nothofagus fusca, compression rolled at high moisture content

Dependent Variable: PRESERVATIVE UPTAKE IN PERCENT
Independent Variable 1: ROLLER DIAMETER (DIAMETER)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
DIAMETER	2375.787	1	2375.787	0.0000	***
COMPR.	9118.227	2	4559.113	0.0000	***
GR.OR.	474.166	1	474.166	0.0000	***
TWO-WAY INTERACTIONS					
DIAMETER and COMPR.	35.571	2	17.786	0.3482	N.S.
DIAMETER and GR.OR.	21.582	1	21.582	0.2579	N.S.
COMPR. and GR.OR.	207.382	2	103.691	0.0024	**
THREE-WAY INTERACTION					
DIAMETER COMPR. and GR.OR.	32.201	2	16.100	0.3846	N.S.
R	530.765	23	23.077	0.1226	N.S.
ERROR	4247.055	253	16.787		
TOTAL	17042.736	287	59.382		

Table 1.212: Dependent Variable: PRESERVATIVE UPTAKE (continue) (WT/WT IN %)

FACTOR: ROLLER DIAMETER (SMALL= 50.6MM; BIG= 206.8MM)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
SMALL	24.97	4.24	0.35
BIG	30.72	3.94	0.33

F = 1.1574; D.F.= 127,127; P = 0.411394 ;
RATIO OF ERROR VARIANCE (E.V.): N.S.

FACTOR: % COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	20.99	4.10	0.42
10%	27.78	4.34	0.44
13%	34.77	3.84	0.39

BARTLETT'S TEST M/C = 1.2594; P = 0.532741;
RATIO OF E.V.: N.S.

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	29.13	4.40	0.37
(CONTROL	7.80)		
FLAT	26.56	3.77	0.31
(CONTROL	6.18)		

VARIANCE-RATIO TEST: F= 1.3584; D.F.= 127,127;
P= 0.086; N.S.

Table 1.213: Dependent variable: PRESERVATIVE UPTAKE (continue)

MEANS

PRESERVATIVE UPTAKE IN PERCENT (WT/WT) IN%

ROLLER DIAMETER	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
(CONTROLS		7.80	6.18)
SMALL	7%	19.59	17.03
	10%	27.30	23.11
	13%	31.06	31.76
BIG	7%	26.11	21.23
	10%	32.06	28.63
	13%	38.65	37.62

GRAND MEAN = 27.85; COEFFICIENT OF VARIATION = 14.71%

Table 1.311:

Summary of ANOVA for testing the effects of three different treatment factors on the permeability characteristics of Nothofagus fusca, compression rolled at high moisture content

Dependent Variable : PRESERVATIVE PENETRATION IN MM
Independent Variable 1: ROLLER DIAMETER (DIAMETER)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
DIAMETER	108.437	1	108.437	0.0000	***
COMPR.	517.690	2	258.845	0.0000	***
GR.OR.	25.597	1	25.597	0.0000	***
TWO-WAY INTERACTIONS					
DIAMETER and COMPR.	8.089	2	4.044	0.0303	*
DIAMETER and GR.OR.	0.728	1	0.728	0.4252	N.S.
COMPR. and GR.OR.	13.778	2	6.889	0.0028	**
THREE-WAY INTERACTION					
DIAMETER COMPR. and GR.OR.	2.241	2	1.121	0.3760	N.S.
R	32.784	23	1.425	0.2039	N.S.
ERROR	288.730	253	1.141		
TOTAL	998.075	287	3.478		

Table 1.312: Dependent Variable: PRESERVATIVE PENETRATION (MM) (continue)

FACTOR: ROLLER DIAMETER (SMALL= 50.6MM; BIG= 206.8MM)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
SMALL	6.32	1.10	0.09
BIG	7.54	0.99	0.08

F = 1.3128; D.F.= 127,127; P = 0.126435;
RATIO OF E.V.: N.S.

FACTOR: % COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	5.32	1.10	0.11
10%	6.87	1.12	0.12
13%	8.60	0.98	0.10

BARTLETT'S TEST M/C = 1.9013; P = 0.386500;
RATIO OF E.V. : N.S.

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	7.23	1.35	0.10
FLAT	6.63	0.97	0.08

VARIANCE-RATIO TEST: F= 1.4412; D.F.= 127,127;
P= 0.0404; *

Table 1.313: Dependent Variable: PRESERVATIVE PENETRATION (continue)

MEANS

PRESERVATIVE PENETRATION IN MM

ROLLER DIAMETER	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
(CONTROLS		1.94	1.54)
SMALL	7%	5.20	4.52
	10%	6.85	5.82
	13%	7.64	7.87
BIG	7%	6.36	5.19
	10%	7.78	7.04
	13%	9.54	9.36

GRAND MEAN = 6.93; COEFFICIENT OF VARIATION = 15.41%

Table 1.411:

Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the drying characteristics of *Nothofagus fusca*, initially at high moisture content

Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (LN M.C. /WEEK)
Independent Variable 1: HOT WATER PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
PRETREATMENT	0.04861	1	0.04861	0.0000	***
GRAIN ORIENT.	0.00241	1	0.00241	0.0032	***
PRETREATMENT and GRAIN ORIENT.	0.00157	1	0.00157	0.0119	**
ERROR	0.00215	12	0.00018		
TOTAL	0.05474	15	0.00365		

FACTOR: PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
HOT WATER PRETREATMENT	-0.2363	0.0166	0.0059
NO PRETREATMENT	-0.1261	0.0091	0.0032

Variance-Ratio Test : F = 3.2955; D.F. = 6,6;
P = 0.1724; N.S.

Table 1.412:
(continue)
Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the drying characteristics of <u>Nothofagus fusca</u>, initially at high high moisture content

Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (LN M.C./WEEK)
Independent Variable 1: PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER-SAWN	-0.1690	0.0082	0.0029
FLAT-SAWN	-0.1935	0.0151	0.0060

Variance-Ratio Test : F = 4.3167; D.F. = 6,6;
P = 0.0984; N.S.

PRETREATMENTS AND GRAIN ORIENTATION MEANS

	QUARTERSAWN	FLATSAWN
HOT WATER PRETREATMENT	-0.2142	-0.2585
NO PRETREATMENT	-0.1238	-0.1285

COEFFICIENT OF VARIATION = 7.39 %

Table 1.511:

Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the permeability characteristics of *Nothofagus fusca*, initially at high moisture content

Dependent Variable : LOG E TRANSFORMED PRESERVATIVE UPTAKE IN PERCENT (WT/WT BASIS)
Independent Variable 1: PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
PRETREATMENT	0.05680	1	0.05680	0.5528	N.S.
GRAIN ORIENT.	0.26871	1	0.26871	0.2019	N.S.
PRETREATMENT and GRAIN ORIENT.	0.08697	1	0.08697	0.4634	N.S.
ERROR	4.40507	28	0.15732		
TOTAL	4.81755	31	0.15541		

FACTOR: PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E
HOT WATER PRETREATMENT	2.08	0.55	0.14
(untransformed)	(8.04)		
NO PRETREATMENT	2.00	0.11	0.03
(untransformed)	(7.39)		

Variance - Ratio Test : F = 1.1645; D.F. = 14,14;
P = 0.0000; ***

Table 1.512:
(continue)
Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the permeability characteristics of *Nothofagus fusca* initially at high moisture content

Dependent Variable: LOG E TRANSFORMED PRESERVATIVE UPTAKE IN PERCENT (WT/WT BASIS)
Independent Variable 1: HOT WATER PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER-SAWN	2.13	0.3813	0.0953
(untransformed)	(8.45)		
FLAT-SAWN	1.95	0.4114	0.1029
(untransformed)	(7.03)		

Variance-Ratio Test : F = 1.1645; D.F. = 14,14;
P = 0.7797; N.S.

PRETREATMENTS AND GRAIN ORIENTATION MEANS

	QUARTERSAWN	FLATSAWN
HOT WATER PRETREATMENT	2.23	1.94
(untransformed)	(9.28)	(6.96)
NO PRETREATMENT	2.04	1.96
(untransformed)	(7.69)	(7.10)

COEFFICIENT OF VARIATION = 19.42%

Table 1.611:

Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the permeability characteristics of <u>Nothofagus fusca</u>, initially at high moisture content

Dependent Variable: SQUARE ROOT TRANSFORMED PRESERVATIVE PENETRATION IN MM
Independent Variable 1: HOT WATER PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
PRETREATMENT	0.04186	1	0.04186	0.4695	N.S.
GRAIN ORIENT.	0.08428	1	0.08428	0.3072	N.S.
PRETREATMENT and GRAIN ORIENT.	0.04590	1	0.04590	0.4490	N.S.
ERROR	2.18007	28	0.07786		
TOTAL	2.35211	31	0.07587		

FACTOR PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
HOT WATER PRETREATMENT (untransformed)	1.44 (2.08)	0.39	0.10
NO PRETREATMENT (untransformed)	1.37 (1.87)	0.08	0.02

Variance - Ratio Test : F = 22.5677; D.F. = 14,14;
P = 0.0000 ; ***

Table 1.612:
(continue)
Summary of ANOVA for testing the effects of a hot water pretreatment and grain orientation on the permeability characteristics of <u>Nothofagus fusca</u>

Dependent Variable: SQUARE ROOT TRANSFORMED PRESERVATIVE PENETRATION IN MM
Independent Variable 1: HOT WATER PRETREATMENT
Independent Variable 2: GRAIN ORIENTATION

FACTOR: GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER-SAWN (untransformed)	1.46 (2.12)	0.2873	0.0718
FLAT-SAWN (untransformed)	1.36 (1.83)	0.2706	0.0676

Variance-Ratio Test : F = 1.1271; D.F. = 14,14;
P = 0.8260; N.S.

PRETREATMENTS AND GRAIN ORIENTATION MEANS

	QUARTERSAWN	FLATSAWN
HOT WATER PRETREATMENT (untransformed)	1.53 (2.34)	1.35 (1.83)
NO PRETREATMENT (untransformed)	1.38 (1.73)	1.36 (1.84)

COEFFICIENT OF VARIATION = 19.87%

Table 1.711:

Summary of ANOVA for testing the effects of three different treatment factors on the drying characteristics of <u>Nothofagus fusca</u> after hot soaking and compression rolling at high initial moisture content

Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (LN M.C./WEEK)
Independent Variable 1: HOT WATER PRETREATMENT (PRETR.)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
PRETR.	0.07423	1	0.07423	0.0000	***
COMPR.	0.00013	2	0.00006	0.8135	N.S.
GR.OR.	0.00361	1	0.00361	0.0014	**
TWO-WAY INTERACTIONS					
PRETR. and COMPR.	0.00384	2	0.00154	0.01129	*
PRETR. and GR.OR.	0.00005	1	0.00005	0.67684	N.S.
COMPR. and GR.OR.	0.00331	2	0.00165	0.00849	*
THREE-WAY INTERACTION					
PRETR. COMPR. and GR.OR.	0.00157	2	0.00079	0.08842	N.S.
ERROR	0.01090	36	0.00030		
TOTAL	0.09689	47	0.00206	0.20602	N.S.

Coefficient of Variation = 9.10%

Table 1.712: Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (LN M.C./WEEK) (continue)

FACTOR: PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
NO PRETR.	-0.1520	0.0176	0.0036
PRETR.	-0.2306	0.0172	0.0035

Variance-Ratio Test : F = 1.0518; D.F.= 18,18;
P = 0.915827; N.S.

FACTOR: % COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	-0.1890	0.0213	0.0053
10%	-0.1924	0.0082	0.0020
13%	-0.1925	0.0197	0.0049

BARTLETT'S TEST M/C = 9.9407; P = 0.006941; *

FACTOR GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	-0.1827	0.0126	0.0026
FLAT	-0.2000	0.0212	0.0043

Variance-Ratio Test : F = 2.8348; D.F. = 18,18;
P = 0.03284; *

Table 1.713: Dependent Variable: REGRESSION ADJUSTED DRYING SLOPE C' (continue)

MEANS

REGRESSION ADJUSTED DRYING SLOPE C' (LN M.C./WEEK)

PRE-TREATMENT	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
NO	7%	-0.1279	-0.1493
NO	10%	-0.1505	-0.1630
NO	13%	-0.1483	-0.1730
YES	7%	-0.2274	-0.2516
YES	10%	-0.2395	-0.2168
YES	13%	-0.2022	-0.2464

Table 1.811:

Summary of ANOVA for testing the effects of three different treatment factors on the permeability characteristics of *Nothofagus fusca* after hot soaking and compression rolling at high initital moisture content

Dependent Variable : PRESERVATIVE UPTAKE IN PERCENT (WT/WT BASIS)
Independent Variable 1: HOT WATER PRETREATMENT (PRETR.)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
PRETR.	3318.672	1	3318.672	0.0000	***
COMPR.	3078.123	2	1539.062	0.0000	***
GR.OR.	177.507	1	177.507	0.0001	***
TWO-WAY INTERACTIONS					
PRETR. and COMPR.	29.940	2	14.970	0.2466	N.S.
PRETR. and GR.OR.	0.170	1	0.170	0.8991	N.S.
COMPR. and GR.OR.	113.685	2	56.843	0.0062	*
THREE-WAY INTERACTION					
PRETR. COMPR. and GR.OR.	123.628	2	61.814	0.0041	**
ERROR	883.370	84	10.516		
TOTAL	7725.095	95	81.317		

Coefficient of Variation = 12.95%

Table 1.812: Dependent Variable: PRESERVATIVE UPTAKE IN% (WT/WT BASIS)

FACTOR: PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
NO PRETR.	30.93	3.22	0.47
PRETR.	19.17	3.27	0.47

Variance-Ratio Test : F = 1.0284; D.F.= 42,42;
P = 0.928187; N.S.

FACTOR: COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	18.49	3.24	0.57
10%	24.36	3.45	0.61
13%	32.31	3.02	0.53

BARTLETT'S TEST M/C = 0.4920; P = 0.781907; N.S.

FACTOR: GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	26.41	3.16	0.46
FLAT	23.69	3.33	0.48

Variance-Ratio Test : F = 1.1103; D.F. = 42,42;
P = 0.73621; N.S.

Table 1.813: Dependent Variable: PRESERVATIVE UPTAKE (continue)

MEANS

PRESERVATIVE UPTAKE IN PERCENT (WT/WT BASIS)

PRE-TREATMENT	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
NO	7%	26.14	22.69
NO	10%	34.30	27.50
NO	13%	36.55	38.40
YES	7%	12.00	13.11
YES	10%	20.22	15.43
YES	13%	29.25	25.02

Table 1.911:

Summary of ANOVA for testing the effects of three different treatment factors on the permeability characteristics of Nothofagus fusca after hot soaking and compression rolling at high initial moisture content

Dependent Variable: PRESERVATIVE PENETRATION IN MM
Independent Variable 1: HOT WATER PRETREATMENT (PRETR.)
Independent Variable 2: COMPRESSION LEVEL (COMPR.)
Independent Variable 3: GRAIN ORIENTATION (GR.OR.)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. F	SIGNIFICANCE
PRETR.	192.497	1	192.497	0.0000	***
COMPR.	193.060	2	96.530	0.0000	***
GR.OR.	10.868	1	10.868	0.0001	***
TWO-WAY INTERACTION					
PRETR. and COMPR.	1.680	2	0.840	0.2857	N.S.
PRETR. and GR.OR.	0.051	1	0.051	0.7812	N.S.
COMPR. and GR.OR.	6.675	2	3.337	0.0085	**
THREE-WAY INTERACTION					
PRETR. COMPR. and GR.OR.	8.267	2	4.133	0.00293	**
ERROR	55.478	84	0.660		
TOTAL	468.576	95	4.932		

Coefficient of Variation = 13.19%

Table 1.912: Dependent Variable: PRESERVATIVE PENETRATION IN MM (continue)

FACTOR: PRETREATMENT

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
NO PRETR.	7.58	0.80	0.12
PRETR.	4.75	0.83	0.12

Variance-Ratio Test : F = 1.0612; D.F.= 42,42;
P = 0.848310; N.S.

FACTOR: % COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
7%	4.52	0.79	0.14
10%	5.99	0.87	0.15
13%	7.98	0.77	0.14

BARTLETT'S TEST M/C = 0.4083; P = 0.815337; N.S.

FACTOR: GRAIN ORIENTATION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
QUARTER	6.50	0.79	0.11
FLAT	5.83	0.84	0.12

Variance-Ratio Test : F = 1.1240; D.F. = 42,42;
P = 0.70669; N.S.

Table 1.913: Dependent Variable: PRESERVATIVE PENETRATION IN MM (continue)

MEANS

PRESERVATIVE PENETRATION IN MM

PRE-TREATMENT	COMPRESSION LEVEL	QUARTER SAWN	FLAT SAWN
NO	7%	6.34	5.56
NO	10%	8.37	6.76
NO	13%	8.97	9.49
YES	7%	2.96	3.22
YES	10%	5.03	3.81
YES	13%	7.33	6.14

Table 2.100:

Summary of ANOVA for testing the effects of the rolling-compression levels on the permeability characteristics of Nothofagus fusca rolled at moisture contents below fibre saturation

Dependent Variable : PRESERVATIVE UPTAKE IN %
Independent Variable 1: COMPRESSION LEVEL
Constants : FEED SPEED (1000 MM/SEC)
LARGE ROLLER DIAMETER
FLATSAWN BOARDS

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. F	SIGNIFICANCE
COMPR. LEVEL	6527.4612	3	2175.8204	0.0000	***
ERROR	498.126	12	41.5105		
TOTAL	7025.587	15	468.3725		

FACTOR: %COMPRESSION

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN V.E.
CONTROL	10.48	4.19	2.10
7%	46.16	4.87	2.44
10%	54.34	9.15	4.57
13%	63.93	6.41	3.20

BARTLETT'S TEST: M/C = 1.9210; P = 0.588971; N.S.

RATIO OF E.V. BETWEEN THE FOUR COMPRESSION LEVELS IS NOT SIGNIFICANT

Table 3.111:

Summary of ANOVA for testing the effects of two different treatment factors on the permeability characteristics of <u>Nothofagus fusca</u>, compression rolled at medium moisture content (60%)

Dependent Variable: PRESERVATIVE UPTAKE IN PERCENT
Independent Variable 1: FEED SPEED (F.S.)
Independent Variable 2: GRAIN ORIENTATION (GR.OR.)
Constant: Compression level (10%)
Roller diameter (206.8 mm)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
F.S.	3032.655	4	758.164	0.0000	***
GR.OR.	311.364	1	311.364	0.0037	**
TWO-WAY INTERACTION					
FEED SPEED and GR.OR.	209.351	4	52.338	1.6614	N.S.
ERROR	945.05	30	31.502		
TOTAL	4498.42	39	115.344		

FACTOR: FEED SPEED (MM/S)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
CONTROLS	6.30	2.843	1.005
500	27.54	9.703	3.431
1000	30.24	4.892	1.730
2000	24.34	1.863	0.659
3000	28.09	5.280	1.867

BARTLETT'S TEST M/C=16.135, P=0.0028,
Error Variance (E.V.) is significant

Table 3.112: (continue)

Summary of ANOVA for testing the effects of two different treatment factors on the permeability characteristics of Nothofagus fusca, compression rolled at medium moisture content (60%)

Dependent Variable: PRESERVATIVE UPTAKE IN PERCENT

FACTOR: GRAIN ORIENTATION (GR.OR.)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
FLAT SAWN	26.09	15.41	3.92
QUARTER SAWN	20.51	47.58	6.89

VARIANCE-RATIO TEST: F=3.087, D.F.= 15, 15
P = 0.0362, Error variance is significant (*)

MEANS

PRESERVATIVE UPTAKE IN PERCENT (WT/WT BASIS)

FEED SPEED (MM/S)	FLAT SAWN	QUARTER SAWN
CONTROLS (0)	7.90	4.70
500	34.56	20.50
1000	31.90	28.56
2000	27.50	21.18
3000	28.58	27.60

Table 3.211:

Summary of ANOVA for testing the effects of two different treatment factors on the modulus of rupture (MOR) of Nothofagus fusca, compression rolled at medium moisture content (60%)

Dependent Variable: MODULUS OF RUPTURE (MOR)
Independent Variable 1: FEED SPEED (F.S.)
Independent Variable 2: GRAIN ORIENTATION (GR.OR.)
Constant: Compression level (10%)
Roller diameter (206.8 mm)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
F.S.	1457.226	4	364.307	0.0533	N.S.
GR.OR.	77.028	1	77.028	0.4733	N.S.
TWO-WAY INTERACTION					
FEED SPEED and GR.OR.	556.041	4	139.010	0.9383	N.S.
ERROR	10370.80	70	148.154		
TOTAL	12461.10	79	157.735		

FACTOR: FEED SPEED (MM/S)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
CONTROLS	116.71	9.238	2.310
500	110.89	16.717	4.179
1000	113.55	8.758	2.190
2000	111.77	11.928	2.982
3000	103.79	12.530	3.133

BARTLETT'S TEST M/C= 7.592, P=0.1077,
Error Variance (E.V.) is not siginficant

Table 3.212: (continue)

Summary of ANOVA for testing the effects of two different treatment factors on the modulus of rupture (MOR) of *Nothofagus fusca*, compression rolled at medium moisture content (60%)

Dependent Variable: MODULUS OF RUPTURE

FACTOR: GRAIN ORIENTATION (GR.OR.)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
FLAT SAWN	112.32	11.36	1.80
QUARTER SAWN	110.36	12.93	2.05

VARIANCE-RATIO TEST: F=1.297, D.F.= 35, 35
P = 0.4462, Error variance is not significant

MEANS

MODULUS OF RUPTURE (N / MM^2)

FEED SPEED (MM/S)	FLAT SAWN	QUARTER SAWN
CONTROLS (0)	115.46	117.96
500	111.18	110.61
1000	115.81	111.29
2000	109.95	113.59
3000	109.22	98.36

Table 3.311:

Summary of ANOVA for testing the effects of two different treatment factors on the modulus of elasticity (MOE) of *Nothofagus fusca*, compression rolled at medium moisture content (60%)

Dependent Variable: MODULUS OF ELASTICITY (MOE) (N/MM^2)
Independent Variable 1: FEED SPEED (F.S.)
Independent Variable 2: GRAIN ORIENTATION (GR.OR.)
Constant: Compression level (10%)
Roller diameter (206.8 mm)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
F.S.	13614327	4	3403581	0.0018	**
GR.OR.	8890445	1	8890445	0.0007	***
TWO-WAY INTERACTION					
FEED SPEED and GR.OR.	5444972	4	1361243	0.1176	N.S.
ERROR	49770067	70	711095		
TOTAL	77719810	79	9837951		

FACTOR: FEED SPEED (MM/S)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
CONTROLS	10484.8	865.1	216.3
500	10121.0	993.1	248.3
1000	9826.0	772.2	193.6
2000	10147.2	860.0	215.0
3000	9255.1	695.9	174.0

BARTLETT'S TEST M/C= 1.929, P=0.7487,
Error Variance (E.V.) is not significant

Table 3.312: (continue)

Summary of ANOVA for testing the effects of two different treatment factors on the modulus of elasticity (MOE) of *Nothofagus fusca*, compression rolled at medium moisture content (60%)

Dependent Variable: MODULUS OF ELASTICITY (N/MM^2)

FACTOR: GRAIN ORIENTATION (GR.OR.)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
FLAT SAWN	10300	847.4	134.0
QUARTER SAWN	9633	839.0	132.7

VARIANCE-RATIO TEST: F=1.020, D.F.= 35, 35
P = 0.9531, Error variance is not significant

MEANS

MODULUS OF ELASTICITY (N / MM^2)

FEED SPEED (MM/S)	FLAT SAWN	QUARTER SAWN
CONTROLS (0)	10643	10327
500	10360	9882
1000	10266	9386
2000	10190	10104
3000	10042	8469

Table 3.411:

Summary of ANOVA for testing the effects of two different treatment factors on the total work to failure (WTF) of *Nothofagus fusca*, compression rolled at medium moisture content (60%)

Dependent Variable: TOTAL WORK TO FAILURE (WTF) (N/MM^2)
Independent Variable 1: FEED SPEED (F.S.)
Independent Variable 2: GRAIN ORIENTATION (GR.OR.)
Constant: Compression level (10%)
Roller diameter (206.8 mm)

Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	TAIL PROB. P	SIGNIFICANCE
F.S.	0.006617	4	0.00164	0.2735	N.S.
GR.OR.	0.000097	1	0.00010	0.7824	N.S.
TWO-WAY INTERACTION					
FEED SPEED and GR.OR.	0.002179	4	0.00054	0.4326	N.S.
ERROR	0.088161	70	0.00126		
TOTAL	0.097053	79	0.00123		

FACTOR: FEED SPEED (MM/S)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
CONTROLS	0.1484	0.0392	0.0098
500	0.1214	0.0412	0.0103
1000	0.1420	0.0233	0.0058
2000	0.1415	0.0230	0.0058
3000	0.1398	0.0446	0.0111

BARTLETT'S TEST M/C= 10.247 P=0.03646,
Error Variance (E.V.) is significant (*)

Table 3.412: (continue)

Summary of ANOVA for testing the effects of two different treatment factors on the total work to failure (WTF) of Nothofagus fusca, compression rolled at medium moisture content (60%)

Dependent Variable: TOTAL WORK TO FAILURE (N/MM^2)

FACTOR: GRAIN ORIENTATION (GR.OR.)

VALUES	MEAN	STANDARD DEVIATION	STANDARD ERROR OF MEAN E.V.
FLAT SAWN	0.1397	0.0303	0.0048
QUARTER SAWN	0.1375	0.0400	0.0063

VARIANCE-RATIO TEST: F=1.740, D.F.= 35, 35
P = 0.1061, Error variance is not significant

MEANS

WORK TO TOTAL FAILURE (N / MM^2)

FEED SPEED (MM/S)	FLAT SAWN	QUARTER SAWN
CONTROLS (0)	0.1418	0.1550
500	0.1276	0.1151
1000	0.1444	0.1396
2000	0.1384	0.1446
3000	0.1464	0.1331

CHAPTER 6: THE ROLLING PROCESS

6.1. THE EXPERIENCE WITH METALS DURING ROLLING

In the experiments on compression rolling described in the bibliography, only limited attention had been given to the analysis of the compression and decompression cycle. This is understandable since timber when subjected to such a dynamic loading process behaves in a very different manner to other materials which are commonly "rolled", such as metals or plastics. Theories concerning the behaviour of these ductile materials during rolling can not easily be applied to a highly anisotropic and elasto-plastic material, such as timber.

It is intended to introduce the rolling process as applied to a plastic material, in this case metal, in order to broadly describe the interaction between rolling equipment and rolled material. The process of rolling plastic materials will be described and the difficulty in developing an equivalent model for timber then becomes apparent.

6.1.1. Metal under static load

When a solid body is subjected to an external force a change in shape occurs; this deformation can be either elastic, if the deformation is recoverable upon removal of the load, or it can be plastic, where a permanent deformation remains after removal of the load.

The characteristic stress-strain relationship for metals subjected to tensile forces is shown in Fig.6.1. Stress, defined as the force acting per unit area, is represented on the ordinate axis while the corresponding elongation is plotted on the abscissa axis. Stresses not exceeding the elastic limit "S" induce elastic strain whereas higher stresses between the lower and upper yield points lead to plastic or irrecoverable strain. The plastic state is defined as: "...The state, in which solid matter can undergo permanent deformation without destruction of cohesive forces.." (Wusatowski, 1969).

Many metals can be strained plastically to a substantial greater extent than elastically; it is then generally assumed that when the strain is large the elastic deformation component can be disregarded. The degree of plasticity of different metals depends on their respective crystallographic structure which determines the slip processes of dislocations during deformation.

S = Elastic limit
Y (PL) = Lower plastic yield point
Y (PU) = Upper plastic yield point
U (T) = Ultimate load to total failure

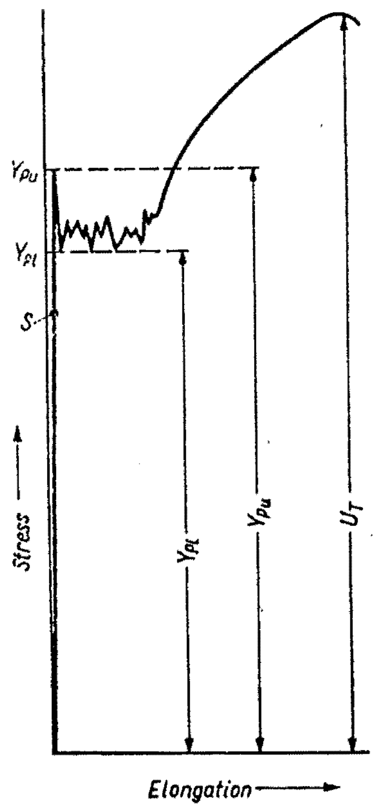
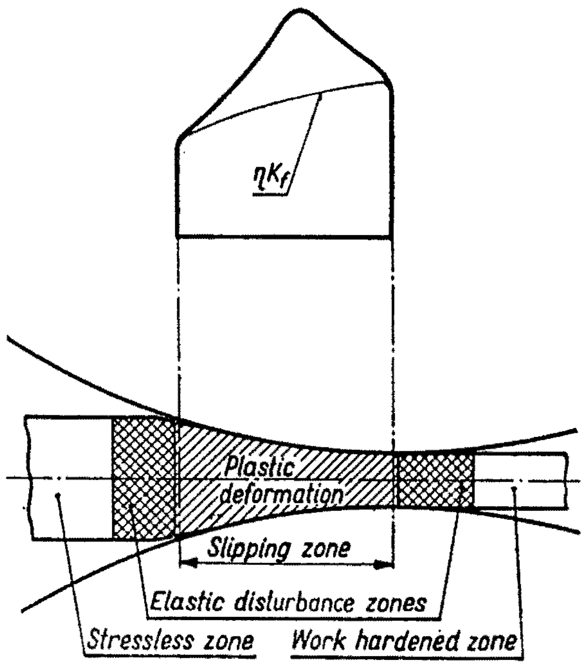


Figure 6.1 Stress-strain diagramm for steel under tensile load (Acc. to Wusatowski, 1969,,p. 3)

6.1.2. On the rolling of metal

In the process of cold rolling the individual crystallites within the metal are not only displaced and oriented according to the externally applied forces but the strained crystallite itself changes shape, becoming more and more elongated; the rolled metal loses its isotropic properties. A schematic figure (Figure 6.2) of conditions arising in cold metal rolling without axial forces acting on the rolled material shows the different stages during the process (Wusatowski, 1969).

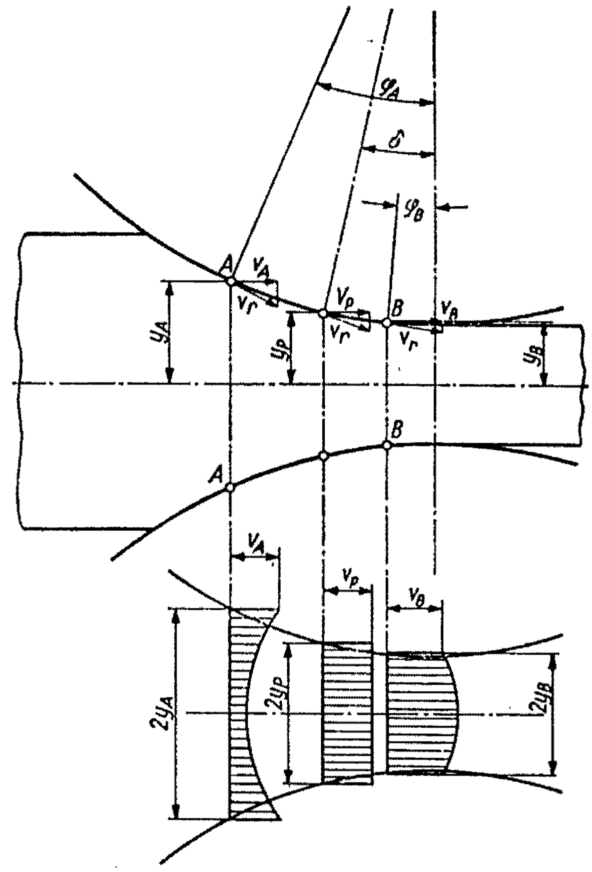


η = coefficient for uniform deformation

η x K(f) = constrained yield stress (yield stress in compression or frictionless rolling

Figure 6.2 Scheme of compression cycle during cold metal rolling (Acc. to Wusatowski,1969, page 208)

The stresses in the various cross sections in the area of plastic deformation are different, due in part to non uniform speed conditions in the compressed material (Figure 6.3.): the metal accelerates while passing between the rollers. This factor as well as varying draft and metal flow is responsible for non uniform stress distribution throughout the material in the plastic deformation zone. Analysis on "Flow of metal in rolling" as presented by Wusatowski in one of his chapters (1969, Chapter 3.3) assumes that the process of rolling induces strain across the entire cross section under compression.



V(r) = Peripheral speed of rolls (m/s)
V(p) = V(r) x cos δ
V(A) = V(r) x cos ϕ_A
V(B) = V(r) x cos ϕ_B
V(Am)= Mean speed of stock in cross section AA
V(Bm)= Mean speed of stock in cross section BB
AA,BB= Arbitrarily chosen planes one on each side of the neutral plane
b = Unit width
2Y(A)= Height of rolled stock before
2Y(B)= Height of rolled stock after
V(S) = Volume per second of rolled stock
= 2 x Y(p) x cos δ
V(Am) < V(A)
V(Bm) > V(B)

Figure 6.3. Speed distribution of metal flow along its cross section (Acc. to Wusatowski, 1969,p 209)

6.1.3. Theories and assumptions

The following simplifying assumptions are made in order to derive slip theories for metal during rolling (Wusatowski, 1951):

"1. Plane and perpendicular cross-sections of the initial stock remain also plane and perpendicular after rolling. Such deformation is called a parallelepiped or homogeneous one, and follows from the assumption that metal slips at every point along the plane of contact, except in the neutral plane.

2. The rolled stock does not spread sideways in rolling.

3. The coefficient of friction between roll and surface of rolled stock is constant at every point along the arc of contact.

4. The constrained yield stress is constant along the arc of contact. Therefore it is assumed that the metal is not affected by work hardening in cold rolling, nor by the variable rate of reduction in hot rolling. This assumption also implies that the temperature of the rolled stock does not vary during a pass.

5. The rolled material is homogeneous. Also its elastic deformation is neglected, in view of the considerable larger plastic deformation.

6. Rolls are rigid and are not deformed during rolling.

7. Stress is acting on each cubic element of any cross section between the rollers....."

These assumptions provide the basis for the development of formulae to determine the parameters to be considered during metal rolling such as roll pressure, torque, work and power.

6.2. ON THE RHEOLOGY OF WOOD

6.2.1. Wood under static load

When timber is subjected to an external force, the resulting deformation is either temporary or permanent. Temporary deformation, which is instantaneously recoverable, is defined as elastic recovery, while retarded recovery still taking place after removal of the load is defined as viscoelastic or creep recovery. For metals and other ductile materials the temporary deformation component, which is considered purely elastic, is negligible in comparison to plastic flow, whereas timber is an elasto-plastic material and temporary deformation requires special attention. One of the main differences to the behaviour of a plastic or ductile material lies in the recovery phase of elastoplastic materials. Timber must be regarded as a material displaying both plastic and elastic characteristics.

6.2.2. Temporary and permanent deformation

When wood is subjected to compressive forces, its characteristic strain-time diagram (Figure 6.4) shows two stages; the first part represents the purely elastic deformation OA, where a linear relationship between stress and strain exists. Stresses above that level lead to non linear creep deformation, AB, which is only partly recoverable on unloading C_1D. The boundary between elastic and viscoelastic strain varies significantly with loading rate, hence the position of A on the y-axis is not fixed.

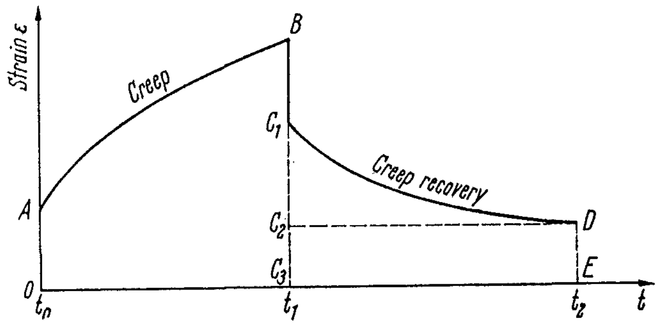


Figure 6.4. Strain-time diagram of wood during loading and unloading cycles (Kollmann, 1961)

On removal of the load, the recovery cycle can be divided into three sections, as illustrated in Figure 6.4.; instantaneous recovery, BC_1, equivalent to the elastic deformation OA, viscoelastic recovery, C_1D, equivalent to a proportion of the total deformation and finally the plastic deformation, or permanent deformation DE. The proportion of viscoelastic recovery in the total recovery is a function of the loading rate; an increase in speed of testing leads not only to higher overall strength values (Kollmann, 1967), but also increases the proportion of elastic to viscoelastic recovery (Kollmann 1961). The effects of loading rate on the instantaneous recovery are represented in Figure 6.5. The graph is derived from compression tests perpendicular to the grain of Picea spp. (Kollmann, 1961), Populus tremuloides (Koch 1964) and from experiments conducted by the author on compression perpendicular to the grain of Nothofagus fusca.

The graph illustrates the relationship between load duration and instantaneous recovery as function of the compression level. For very short loading periods in the order of fractions of a second the elastic recovery is substantial even at compression levels which induce strains well above the commonly defined elastic strain limit of timber. In the course of compression rolling experiments the complete loading cycle never exceeds 3 seconds, depending on the feed speed and the roller diameter and would typically be of the order of 0.2 to 0.02 seconds. For example, after dynamic compression to 85% of its original thickness the wood will recover to 98.5%. In other words only 10% of the dynamic compression is not recoverable (Cech, 1971).

In the analysis of rolling of wood it will therefore be assumed that creep deformation can be neglected and that the cellwall matrix behaves as a perfect elastic material.

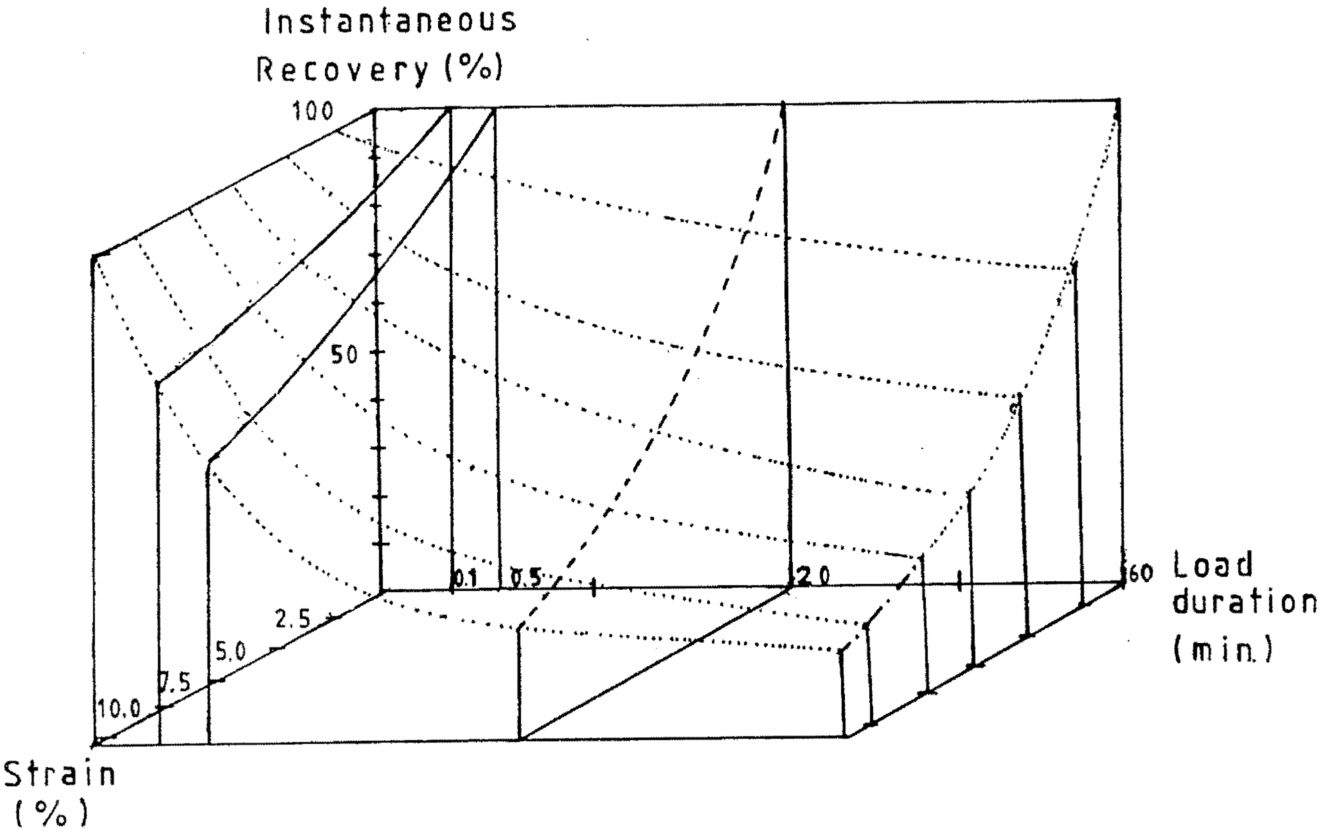
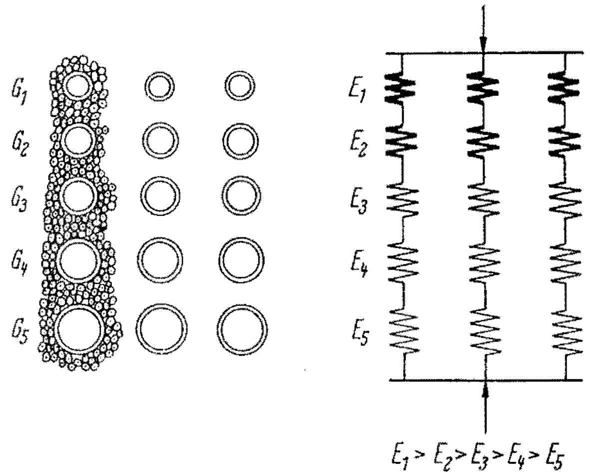


Figure 6.5 Effects of loading time and compression level on instantaneous recovery of timber compressed perpendicular to the grain

Data for Nothofagus (Guenzerodt): ————
Data for Picea (Kollmann): - - - -
Data for Populus (Koch): —·—·—·
Extrapolated Data: ....

6.2.3. Kollmann's model

The rheological models suggested by Kollmann (1961) wood loaded perpendicular to the grain describe wood as a combination of elastic regions of varying stiffness. The pattern of deformation is determined by the alignment of these regions to the direction of the applied load. They can either be arranged in series, in parallel, or in some more complex combination. First, Kollmann considers a purely elastic description where he compares the structural elements of wood with a system of interconnected springs of varying stiffness, associating the more flexible springs with softer sections in wood, while the stiffer springs simulate the behaviour of stronger sections (Figure 6.6.); these would correspond to earlywood and latewood respectively. Stiffness is commonly expressed by the modulus of elasticity (MOE) of the material and calculated from the linear relationship between the elastic stress "σ_E" and the elastic strain "ε_E". Localized density variations result in corresponding variations in the localized MOE which in turn are responsible for variations in strain throughout the sample. As a result inhomogeneous deformation occurs during loading.



$E_1 - E_5$ = Modulus of Elasticity of springs representing the stiffness of vessel elements and surrounding tissue G_1, G_2, G_3, G_4 and G_5

Figure 6.6. Scheme comparing the distribution of vessels in a diffuse porous timber with the rheological model of interconnected springs (Kollmann, 1961)

The assumption for this model is nonetheless that all sections behave perfectly elastically and strain does not exceed the elastic limit in any part of the body. This is strictly applicable only for timber under strains less than about 1% and for short loading periods. For stresses above the limit of elasticity the strain-distribution is influenced by an increasing viscoelastic strain component, " ε_V ", and the plastic strain component, " ε_P ". The total deformation or the total strain, " ε_T ", is therefore defined as:

$$\varepsilon_T = \varepsilon_E + \varepsilon_V + \varepsilon_P \quad \text{(Equation 6.1.)}$$

he elastic strain component is defined by Hooke's Law as irectly proportional to " σ_E " and inversely proportional o the MOE (Kollmann, 1961):

$$\varepsilon_E = \sigma_E / MOE \qquad \text{(Equation 6.2.)}$$

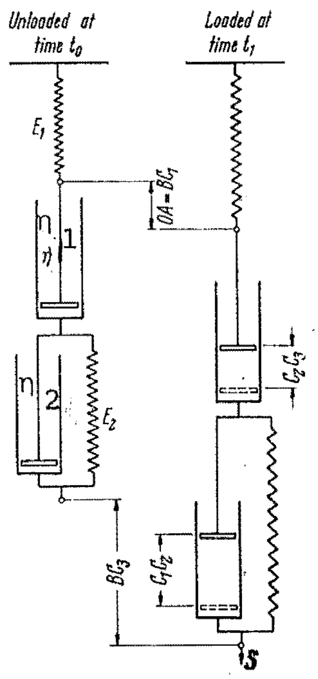
he viscoelastic and plastic strain components follow laws f rheology for viscous materials or Newtonian liquids, here the rate in change of strain "d ($\varepsilon_V + \varepsilon_P$)" is irectly proportional to the stress, " σ " and the time ifferential " dt ", and inversely proportional to the iscosity " η " (Kollmann, 1961):

$$\frac{d}{t}(\varepsilon_V + \varepsilon_P) = (\sigma \times dt)/ \eta \qquad \text{(Equation 6.3.)}$$

ince both plastic and viscoelastic deformation are unctions of time, the mechanical properties of timber are ependent on the duration of load, which is considered in model suggested by Schmidt and Marlies (1948).

.2.4. Schmidt - Marlies' approach

ollmann's simplified model of wood under transverse oading conditions is only strictly applicable for low trains and short load durations. A more comprehensive odel as suggested by Schmidt and Marlies (1948) describes he behaviour of a high polymer by including the viscous lement, where its rheological behaviour is described by a ashpot. As with Kollmann, the elastic deformation component is represented in their model as a spring, whose stiffness is determined by the MOE of the respective section under load (Figure 6.7.). Elastic and viscous elements act together in series and parallel to each other as illustrated in the following scheme:



E(1) = Modulus of elasticity of structural element 1
E(2) = Modulus of elasticity of structural element 2
η_1 = Viscosity of cylinder 1
η_2 = Viscosity of cylinder 2
t = time

Figure 6.7 Schematic representation of Schmidt-Marlies model of wood prior and during loading in tension (Symbols used as in Figure 6.4 , from Kollmann, 1961)

Based on this model the authors present an equation, describing the deformation of wood under load in tension:

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1-\varepsilon^{-\frac{E_2 t}{\eta_2}}\right) + \frac{\sigma}{\eta_1} x \quad t \qquad \text{(Equation 6.4)}$$

where

$$\frac{\sigma}{E_1} = \varepsilon_E; \quad \frac{\sigma}{E_2}\left(1-\varepsilon^{-\frac{E_2 t}{\eta_2}}\right) = \varepsilon_V; \quad \frac{\sigma}{\eta_1} x \ t = \varepsilon_P$$

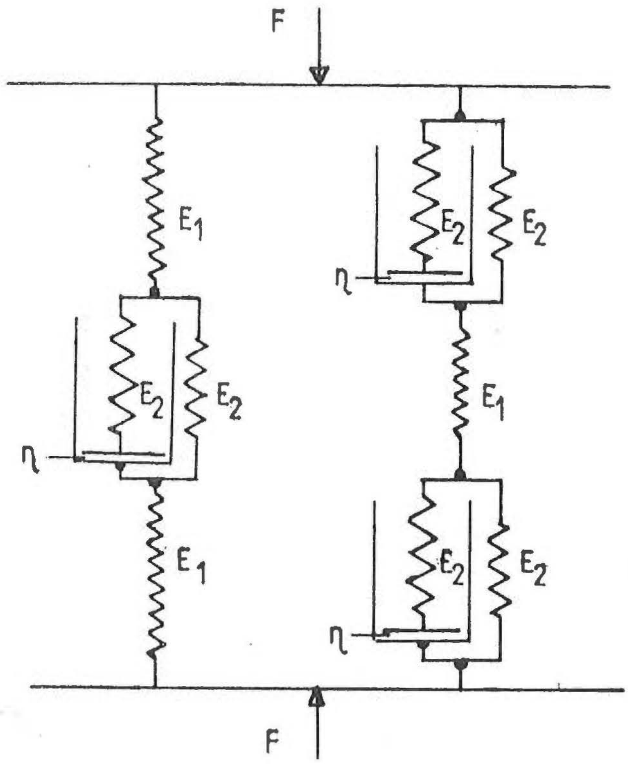
Both viscoelastic and plastic deformation components are functions of time (t) and of the viscosity (η) of the cell wall matrix, which is the principal structural element in wood with load carrying capacity. The Schmidt-Marlies model assumes that the cell voids do not contribute significantly to the strength properties: this is a valid assumption for loading conditions where free movement of displaced cell void contents is possible. The role of the structural elements of the cell voids (cell walls and tyloses), which are summarized in this work as "void envelope" and the mechanical response of the cell lumen contents becomes more important where the free movement of fluid is obstructed by blockages (tyloses, aspirated pits, resins or other cell lumen contents). This aspect of mechanical behaviour is then more comparable to a closed cell foam.

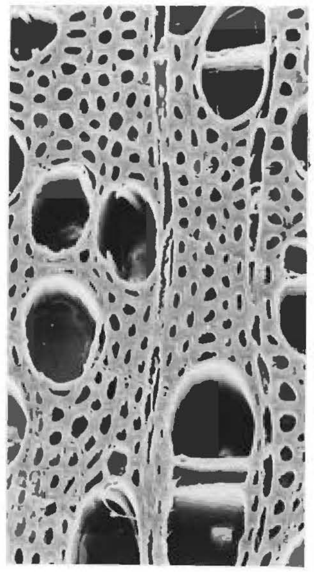
6.2.5. Wood as a closed cell elastic body

The two rheological models discussed so far were developed on the basis that the reduction in volume ocurring in the course of any of the described loading proceedures has no influence on the internal pressure within void spaces. Hence the models can only be applied in the case of highly permeable timbers, which do not offer substantial resistance to fluid flow under a pressure gradient. If these conditions are not fulfilled and stresses are applied causing strain in the timber, which lead to a major reduction in void volume, a further strain component "ε_I" is introduced. "ε (void) is the result of three interactive strain components: deformation of the void envelope "ε_{ENV}", deformation of the liquid "ε_{LIQ}" in the lumen and deformation of the gases in the lumen "ε_{GAS}".

Neglecting "ε_V" and "ε_P" in Equation 6.1 (their contribution to the total deformation at high strains becomes very small compared with "ε_I"), the introduced strain component due to pneumatic loading of the cell luminae, "ε_I" has then to be considered.

Deformation will be controlled by the strain components "ε_{ENV}" and "ε_{GAS}", unless the voids are saturated with an uncompressible liquid. In the latter case the resistance of the liquid to compression leads to its displacement from the voids causing severe damage to the tissue (Figures 6.14 and 6.15). We may neglect " $\dot{\varepsilon}_{LIQ}$ " for wood at lower saturation levels with sufficient compressible gas volume in the voids in a model derived from Kollmann (1968) which should give an approximate idea about the deformation of wood considering the pneumatic effect and disregarding viscoelastic and plastic deformation components of the cell wall matrix (Figure 6.8). The dashpot-spring combination simulates the phenomenon occurring during the compression of voids, the dashpot representing the loss of pressure in the compressed cell lumen due to fluid displacement, while the spring in the dashpot describes the elastic deformation component recoverable due to the remaining pressure. Total recovery of deformation after removal of the load will be primarily a function of the recovery of the cell void envelope. It will be also influenced by the loading rate and the viscosity (compressibility) of the cell void content.





E_1 = MOE of cell wall matrix

E_2 = MOE of cell void envelope, comprising primarily walls of sap conducting cell elements and blockages within these cell types

η = Viscosity of void content

Figure 6.8. Deformation of wood (at low levels of saturation) in compression perpendicular to the grain under consideration of the effect and excluding viscoelastic and plastic strain components within the cell wall matrix. The response to loading of the fibres and of the vascular regions differs, the fibres being stiff while the vessels are elastically weak and deformable. The degree to which they deform depends on the void contents which are either sap and/or gases. The void space will deform or collapse depending on the viscosity of the fluids (liquids and gases) and on the permeability of the vascular system. At high loading rates it can be expected that this system could support higher pneumatic loads.

As mentioned earlier, the compressibility of the cell voids is largely influenced by their contents. If the cell lumens are completely or to a high percentage filled with relatively incompressible substances, the elastic deformation (the stretching of the cell void envelope without collapsing) will be dictated by the maximum yield stress of the weaker material. Consequently wood with higher resistance to circulation of fluids through its void space (as observed in earlywood of Picea sitchensis and described in chapter 7) is expected to resist greater short term loads due to the more pronounced damping effect than more permeable timbers of comparable density. This

A similar phenomenon is described in studies with closed cell polystyrene samples which are generally regarded as viscoelastic (Meinecke and Clark, 1973), " Besides the hysteresis of the viscoelastic polymer in the matrix, there is also the physical process of forcing fluids (gasses or liquids) in and out of the foam. This process is termed pneumatic or liquid damping ". As the theories developed to explain the damping behaviour of closed cell foams could be applicable to wood the following experimental conditions would have to be considered:

1. Flow of fluid through the cells is restricted because of partial blockage of pathways.

2. The cellular matrix yield stress is not exceeded, hence

the intracellular pressure induced strain is completely recoverable and can be considered elastic.

3. The load duration is kept low, preferably under 1 second.

4. Wood is loaded in compression perpendicular to the grain.

5. Moisture content of the specimen is kept constant.

6.3. ON THE ROLLING OF WOOD

6.3.1. Applicability of metal rolling theories

The deformation of wood during rolling is very different to that observed with metals, because of wood's elastic and viscoelastic properties described previously. Also there is a volume change of the body when rolling wood, which does not occur with metals. The following factors make the model derived for metal rolling inapplicable to timber, since elastoplastic materials (timber represents such a material) behave differently when subjected to the multiaxial forces during compression rolling.

1. Constant volume may not be assumed.

2. Wood does not accelerate through the rollers as it is inextensible , to a first approximation in the longitudinal direction and fibres are orientated parallel to the feed direction.

3. The rolled material is inhomogeneous and anisotropic in its three main directions.

4. Elastic deformation is substantially larger than plastic deformation.

5. Not all cubic elements are under triaxial stress during rolling.

6. The constrained yield stress "η x Kf" across the thickness of the sample and along the arc of contact varies, because of the phenomenon of short term surface densification.

7. There are localized density variations in the wood with corresponding fluctuation in MOE, hence the strain is non uniformly distributed.

In the following subchapter the intention is to describe in detail how wood behaves during rolling, and which physical laws can be applied to explain the observed phenomenon.

6.3.2. The deformation of wood during rolling

The behaviour of wood during rolling is comparable with that of a bundle of soda straws glued together, as suggested by Johnston - St Laurent, (Figure 6.9).

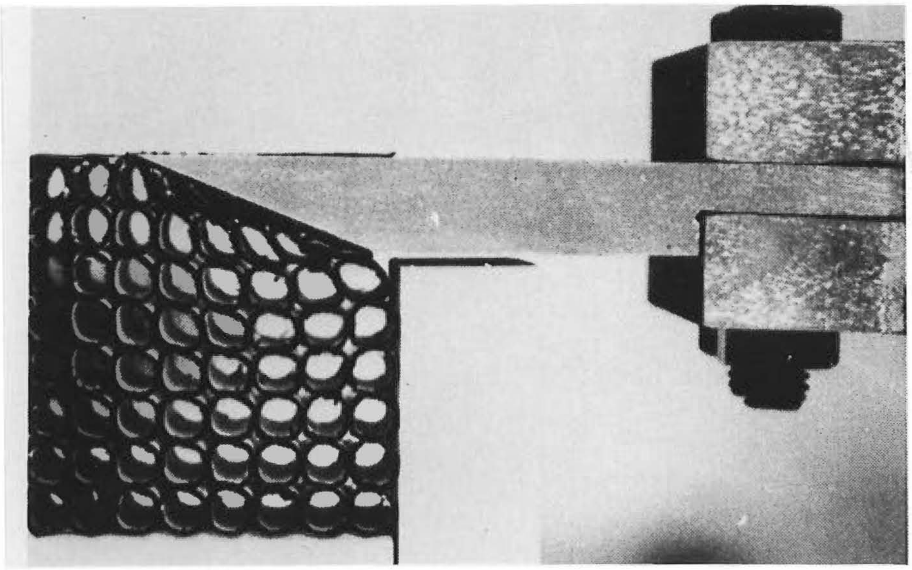


Figure 6.9. The deformation of a bundle of joined straws under sliding compression (according to Johnston-StLaurent, 1978)

This simplified model of the timber is only applicable considering the assumptions, made for the derivation of Equation 6.6.:

1. Load is applied in compression perpendicular to the grain.

2. The cell void volume is substantially greater than the cell matrix volume.

3. Short duration of load.

4. High compression levels.

5. Negligible viscoelastic deformation component arising from creep in the cellular matrix.

Compression rolling cannot be regarded as a uniaxial loading system since, in addition to compressive forces perpendicular to the grain, the material is subjected to shear stresses and axial tensile and compressive stresses induced through the indentation of the roller. The resulting strains, arising from stresses other than from simple compression acting perpendicular to the grain, primarily affect the cell matrix, which can only resist strain levels under 1% if complete elastic recovery is expected. A schematic representation of the deformation and recovery cycle during rolling based on our observations and compared with experiences of other workers (Cech, 1968, Peters and Zenk, 1968) gives an approximate indication of the strain distribution (Figure 6.10.).

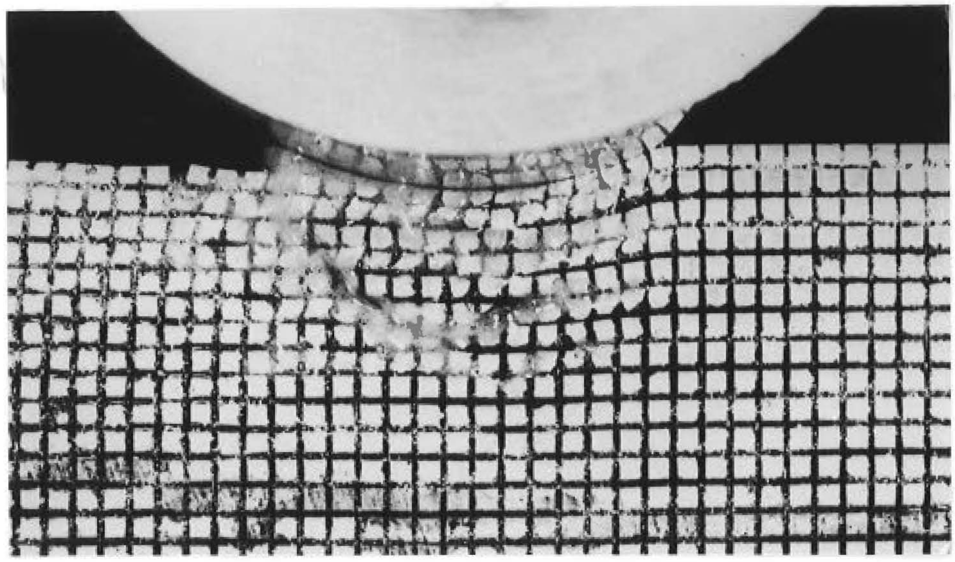


Figure 6.10. Deformation of wood at high compression perpendicular to the grain during rolling with the fibres oriented tranverse to the feed direction as observed by Peters and Zenk in their compression tests with non self powered rolls, (Peters and Zenk, 1968)

At compression levels substantially greater than the limit of elasticity of the cell wall matrix, most of the strain is dissipated in the more compressible cell void space, hence with increasing compression levels the total deformation "ε_T" becomes primarily a function of "ε_{Env}".

The multiaxial stress components acting on the cellwall matrix are therefore not considered in the interpretation of Johnston - St Laurent's model. Greatest attention should be given to the particular distribution of the total deformation, which is restricted to the regions in immediate contact with the surface of the tool. The concentrated deformation in the upper and lower surface of the board can be described as a surface phenomenon. This has been observed during wood deforming processes under static loading conditions (Kollmann, 1959; Doyle, 1980) and under dynamic loading processes (Johnston - St Laurent, 1978; Peters and Zenk, 1968; Grosditz, 1979; Cech, 1972). Further evidence is given in Figure 6.11 , which reveals the compression/decompression cycle during rolling of Red Beech (Nothofagus fusca). The quartersawn board is marked on one of its edges with a grid pattern of overlapping circles, which precisely demonstrates where the deformation occurs.

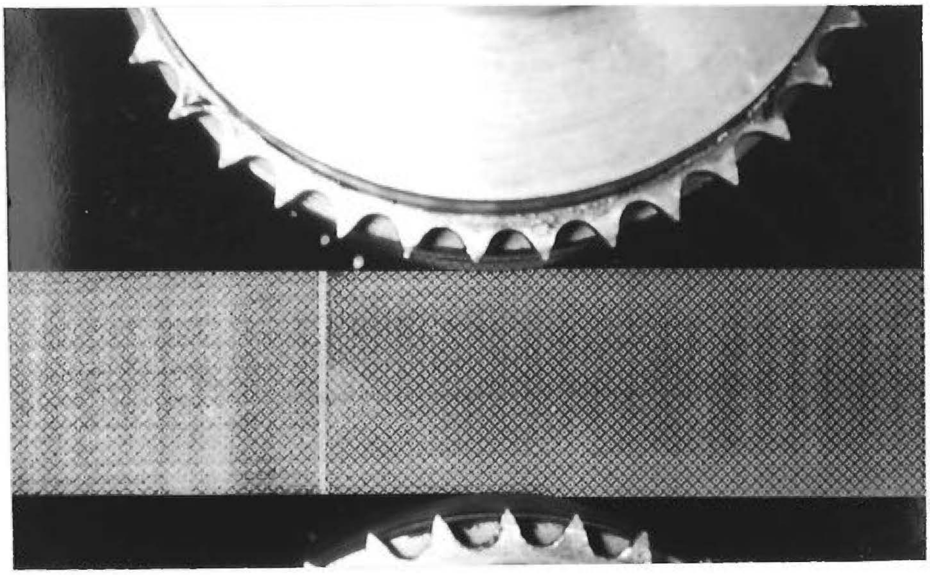


Figure 6.11 Grid pattern marked on edge of board illustrating the deformation geometry during compression rolling (Large roller size, 10% nominal compression, 1000 mm/min feed speed Noth. fusca heartwood, 2 x magnification)

A direct comparison between the photograph of the deformed wood and Johnston-St Laurent's model demonstrates that the deformation is similar in both. The model is only describing conditions arising from rolling in the transverse direction, rather than axially as shown in Figure 6.11. Assuming a constant coefficient of friction between wood and steel in all fibre directions (McKenzie and Karpovich, 1968) axial rolling, or sliding induced compression, deforms primarily the cell voids, but the stress effects on the cellwall matrix will vary, according to the density variation within the timber and the orientation of the annual growth rings.

6.3.3. Considerations of fluid mechanics

While conventional compression tests can be regarded as a uniaxial loading system, where the pneumatic deformation component does not play a significant role, in compression rolling void deformation cannot be ignored. The resistance of different elements of the timber structure to the compression of the voids and the partial displacement of the void contents determines the condition for flow, nominally described by Poiseuille's equation (Stamm, 1967):

$$V = (n \times \pi \times r^4 \times P) / 8 \times \eta \times L \qquad \text{(Equation 6.8.)}$$

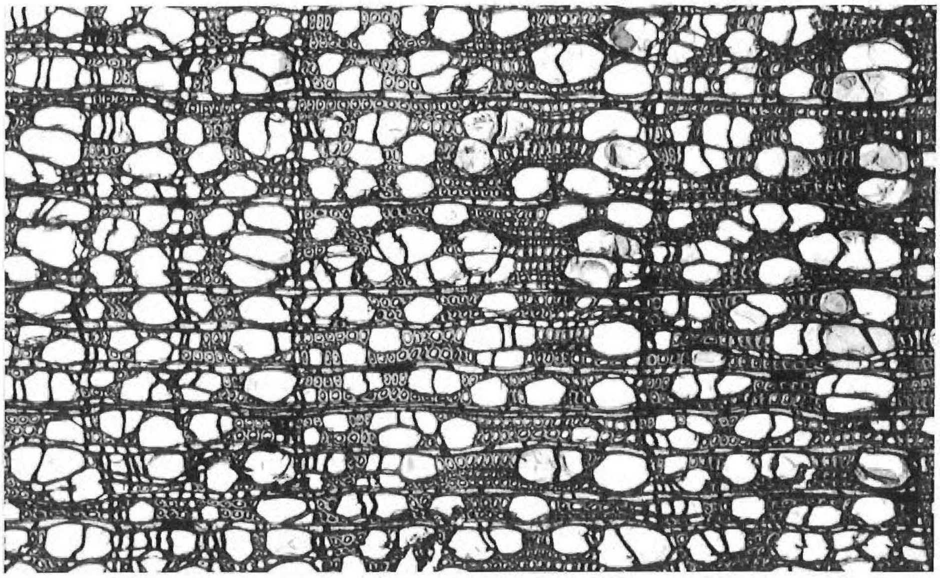
,where V = Volume of flow ; P = Pressure drop
n = number of capillaries; L = Length of capillary
r = mean capillary radius; η = Viscocity

Poiseuille's law assumes that, the capillary radius is constant, which is not strictly true for wood since the capillaries are not continuous but interrupted through blockages. The degree of blockage determines the overall permeability characteristics of a species which is defined as "..the ease with which fluids pass through under an applied pressure gradient.." (Kininmonth, 1970). Since a change in internal pressure is a function of volume, (P x V = constant), the reduction in void volume during compression determines the initial pressure change. In addition to this initial pressure change rolling compression gradually displaces the field of maximum pressure (or maximum deformation) along the board. This generates a pressure wave, which can then be considered as a travelling or dynamic pressure gradient.

6.3.4. Consequences of fluid displacement for wood anatomy

The comparison of wood with Johnston - Laurent's model of straws has to be regarded with caution, because one of the prin-ciple assumptions that the void volume greatly exceeds the cellwall matrix volume is only applicable for timbers of low density. The deformation during rolling is a function of the proportion of "compressible" void volume to the total deformed volume. A further factor to be considered is the distribution of of voids throughout the compressed area.

The cross section of a board of Red Beech contrasts to the simple model of Johnston - St. Laurent and is "made up" of three principal cell types: vessels, fibres and axially and radially orientated parenchyma (Figure 6.12).



Growth ring Growth ring Growth ring

Figure 6.12 (100 x magnification) Light microscopic view of cross section of red beech showing three annual growth rings (GR) and the distribution of the three cell elements: vessels (V), fibres (F), parenchyma (P)

In Figure 6.12, the distribution of the different cell types over the cross section is typical for a diffuse porous timber, but in detail is characteristic of an individual species. The principle cell elements contributing to the void volume, the vessels, are evenly distributed throughout an annual growth ring in Nothofagus fusca, although a decrease in diameter in the latewood occurs. Timbers categorized as semi-ring porous and ring porous show a more pronounced difference in vessel size and vessel distribution throughout a growth ring, and most of the cell void is concentrated in the earlywood.

From Figure 6.12. it can be assumed that the total void volume in N. fusca is evenly distributed throughout the section. A quantitative representation of the contribution of the cell types to the total void indicates the importance of vessels for flow:

	VESSELS		FIBRES	
	Lumen radius	Cellwall thickness	Lumen radius	Cellwall thickness
Dimensions (in um)	7.85	0.785	0.0386	0.1970
Ratio of lumen to cell wall matrix	10	1	1	5
Number of cell elements per mm .. cross section	79	79	1413	1413
Proportion of CE volume to total volume per cross section (%)	93.5		6.5	
		18.8		81.2
Proportion of void and cell wall in unit cross section (%)	60.3	6.0	5.5	27.5

Table 6.1 Distribution of cell elements in a 1 mm^2 cross section of Nothofagus fusca

Primarily, the anatomy of the vessels, which contribute 93.5% to the total void, is of importance for fluid flow induced through rolling. The small total fibre lumen volume (6.5% of total void volume) and the low frequency of pits in the fibre walls minimises its contribution to void content displacement to a neglible amount (Table 6. 1). Vessels in Nothofagus fusca, as described by Meylan and Butterfield (1978) "....are distributed more or less evenly throughout the growth ring though they are usually larger in the earlywood, solitary or occasionally in radial multiples of 2 - 6 cells or clusters of 2 - 4 cells ...". They are axially connected through simple or scalariform perforation plates, while transverse connection is guaranteed through an abundant system of simple vessel to vessel pits. The heartwood vessels are frequently blocked with cellulosic material originating from adjacent parenchymatic cells, which are termed "tyloses" (Figure 6.13).

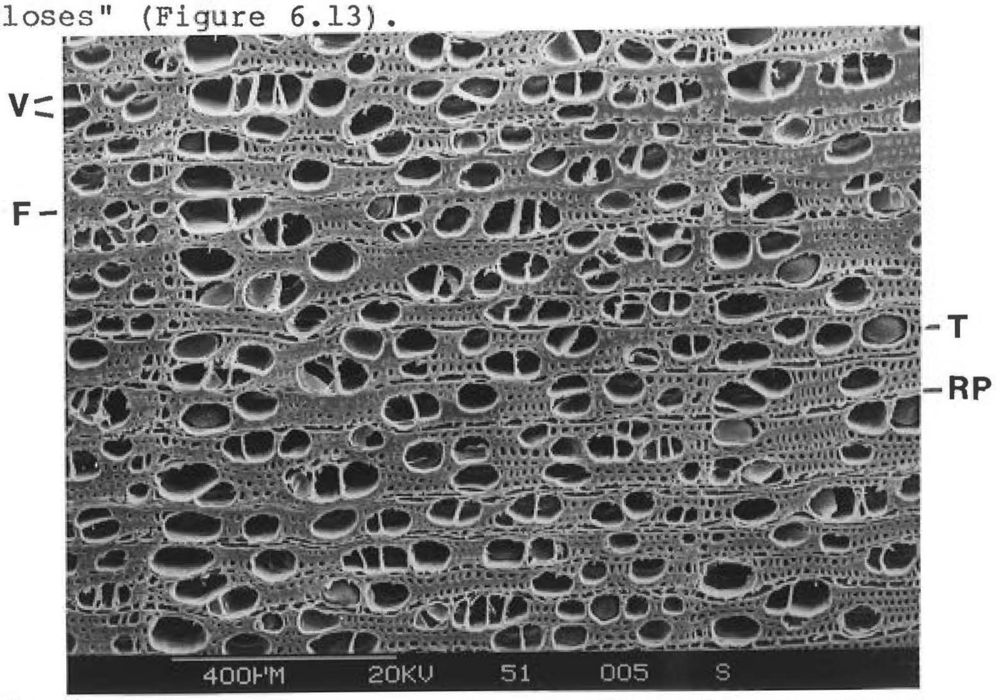


Figure 6.13. Scanning electron micrograph of a cross section of Nothofagus fusca, showing vessels (V), fibres (F), ray parenchyma (RP) and tyloses (T)

When this complex system of interconnected elastic tubes is subjected to a dynamic pressure gradient or pressure wave, the damage is primarily directed to the weaker parts of the structure, namely on the perforation plates, tyloses and the vessel to vessel connecting walls. The compressibility of the cell voids represented in the model (Figure 6.8) as a spring and a dashpot in series will then be a function of the viscosity of the cell void content and of the cell envelope strength characteristics. The stress concentration arising from compressive forces and intracellular pressures cannot be separated and hence the exact strain distribution can not be determined.

Experiments conducted with Nothofagus fusca at different moisture contents revealed that the degree of saturation of the timber has a significant influence on the rolling process. High saturation level reduces the compressibility of the cell voids and fracture occurs in areas of stress concentration. The fracture of the brittle axial and transverse blockages (tyloses, pits and perforation plates) cannot release the total internal pressure, the stress propagates and causes substantial damage to the cell wall matrix, as can be seen in Figure 6.14. and Figure 6.15..

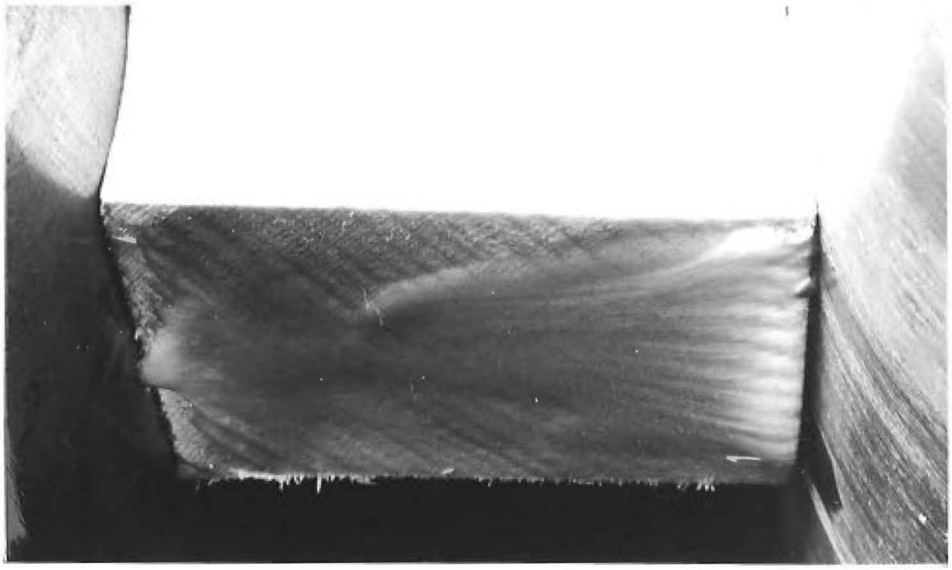


Figure 6.14. 4 x magnification, micrograph of cross section of Nothofagus fusca rolled at 13% compression level when the initial saturation exceeds 90%. The flatsawn board is substantially damaged by displacement of sap in tangential and radial direction

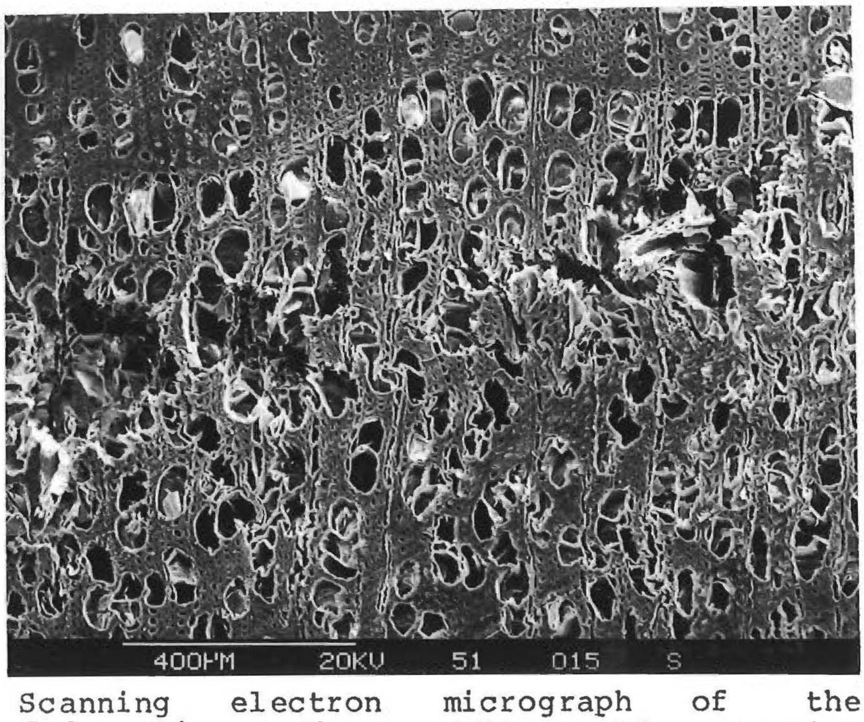


Figure 6.15. Scanning electron micrograph of the deformation of vessels and partial destruction of the cell wall matrix between earlywood vessels

This has also been described by Haslett, who observed similar effects in the course of his experiments (Haslett and Kininmonth, 1975). On the other hand when the moisture content of the timber is below fibre saturation the cell voids are more compressible and same levels of compression as applied to the highly saturated samples do not increase the intra-cellular pressure during rolling to the same extent. The rupture of axial and transverse non-structurally relevant blockages will then be sufficient to relieve the dynamic pressures within the vessels while the stress on the main cellwall matrix remains below the maximum yield stress. Figure 6.16 illustrates the limited damage visible in the vessel lumen, where only tyloses appear to be ruptured:

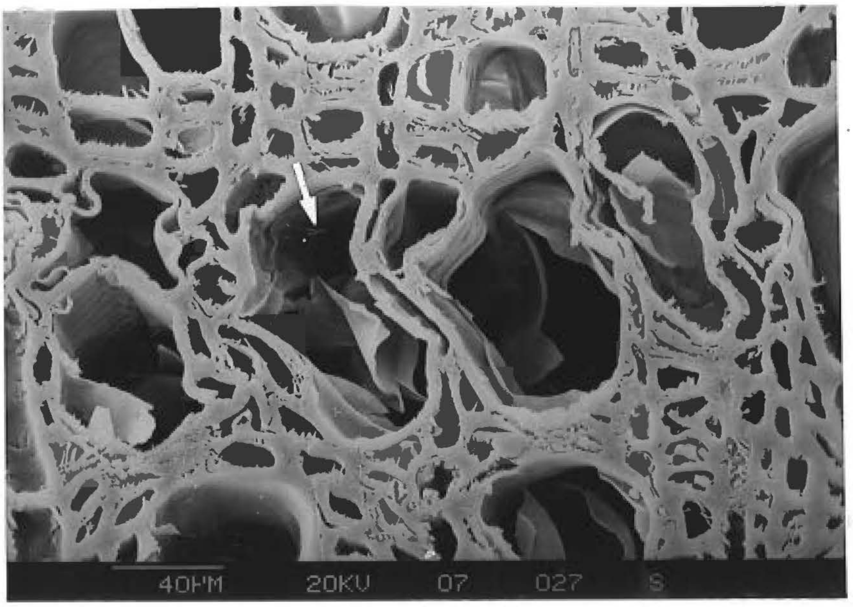


Figure 6.16 Scanning electron micrograph of a cross section of Nothofagus fusca, after rolling at the 13% level, at a moisture content of 20%. Compression was applied in the radial direction. Damage is limited to the vascular area (arrow)

This phenomenon is also characteristic for closed cell foams, described by Kosten and Zwickers in 1938 (from Meinecke and Clark, 1973) as "pneumatic damping". They report an increase in resistance to flow with increase in loading rate, since "...the air of the system gets compressed before it has a chance to flow..."

6.3.5. Implications for rolling related parameters

It has been demonstrated, that the rolling of wood is influenced by a series of factors, which are to a certain extent controllable (by varying compression level, feed speed or moisture content). Models developed in order to predict the rheology of timber can only find limited application, since they are based on conventional strength tests under uniaxial loading conditions. It is further assumed that the degree of open connections within the cellular void system (permeability) does not significantly influence the general strength characteristics of timber. However the role of permeability is not negligible during rolling, as described above. The comparison of this characteristic of timber with the rheological behaviour of foams was considered appropriate to illustrate the process of deformation.

The main component of stress resulting from the pure compressive forces during reduction in thickness of the board is primarily dissipated in the cell wall and hence is a function of the yield point of the latter. The additional stress component resulting from increased internal resistance due to reduction in volume and increased intra-cellular pressure has then to be considered, although its effect can only be estimated. It has been demonstrated earlier that the total strain during rolling is limited to the zones adjacent to the rollers, reducing the volume of voids by different amounts (Figures 6.9 and 6.10).

It has been shown in Figure 6.3 that during metal rolling the speed of flow throughout a cross section of rolled stock varies significantly. To a very limited extent this also applies to timber where the indented surfaces are forced to travel a slightly greater distance in the same time than the undeformed layers in the center of the board. Very high compression levels applied by small diameter, non powered rollers (Figure 6.9), cause a momentary change in speed decelerating the surface layers during the infeed cycle. A consequence is a high tensile stress in the surface which can lead to rupture. Surface stresses gradually relax on the outfeed side of the rollers.

The temporary strain in the wood resulting in a short term change in volume is the fundamental difference between the behaviour of wood and metal during rolling. Metal does not change its volume in any stages of compression and the resulting change in shape remains permanently.

Irregular void distribution in wood and consequential inhomogeneous strain distribution, where some cells might be compressed to 10% of their original volume while others might not be effected at all, is one of the principal reasons, why a precise stress-strain analysis of the rolling process was not attempted in the course of this study. Thus in Figure 6.10 we see that the grid circles are not progressively deformed as one goes from the board centre towards either face, but there are localized bands where deformation is extensive (marked by arrows in the figure). Deformation is in the first place a surface phenomenon, although extreme differences in density within boards of some woods (namely softwoods with very low dense earlywood and dense latewood) can cause localized deformation at a greater distance from the surface (see Figure 7.53A).

CHAPTER 7: IMPLICATIONS OF THE ROLLING PROCESS FOR THE TIMBER

7.1. EFFECTS ON THE ANATOMY OF NOTHOFAGUS FUSCA

In the process of rolling, timber is unevenly deformed with most of the deformation occurring in the regions close to the indenting roller surfaces. Within these regions the strain is also inhomogeneous and to a great extent restricted to the more deformable spaces, namely earlywood and latewood vessels (the case of a diffuse porous hardwoods such as red beech). A displacement of vessel contents (liquid and gases) is induced, which is assumed to follow the principal paths of flow, as described by Siau (1971), Figure 7.00:

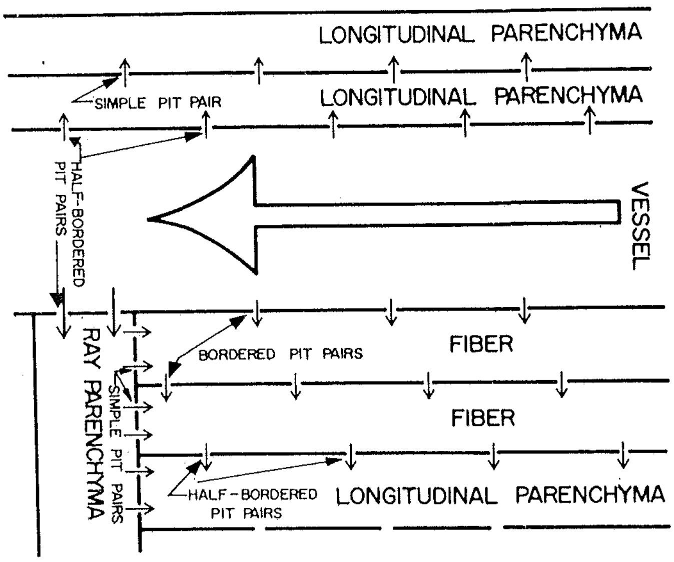


Figure 7.00 Flow paths in hardwoods (according to Siau, 1971)

Flow in hardwoods occurs in the first place through vessel elements and axial parenchyma, and to a lesser extent through fibres and radial parenchyma. In the case of <u>Nothofagus fusca</u> heartwood flow of fluid is severely restricted since:

- the majority of the vessel elements are occluded by tyloses
- longitudinal parenchyma are scarce and often absent
- vessel to ray pitting is limited to terminal ray cells
- ray to ray parenchyma cell wall pitting is occluded by extractives lining the cell lumen

Figures 7.01 and 7.02 show micrographs of <u>N.fusca</u> heartwood, with noticeable occlusions in the vessels as observed in unrolled controls. During compression rolling these pathways suffer substantial alterations, which are described below: Observation with the scanning electron microscope (SEM) of <u>N.fusca</u> after compression rolling revealed substantial damage primarily to the tyloses and vessel walls, while occasionally terminal ray-parenchymatic cells were affected. Figures 7.03 - 7.11 are representative of the damage pattern in sections prepared from the deformed layers of compression rolled boards of <u>N.fusca</u>.

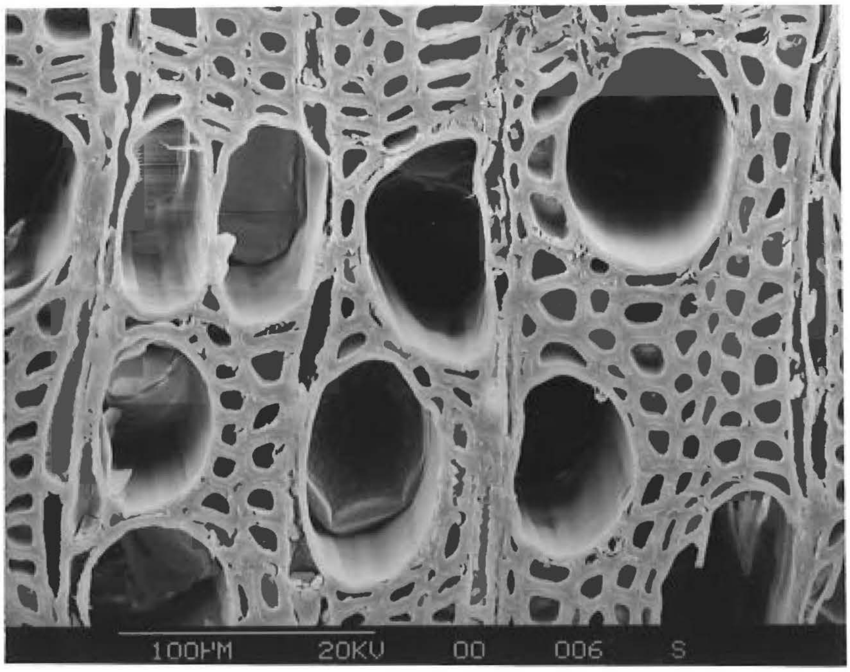


Figure 7.01 SEM; Cross section and view of N.fusca with tyloses occluding vessels in control

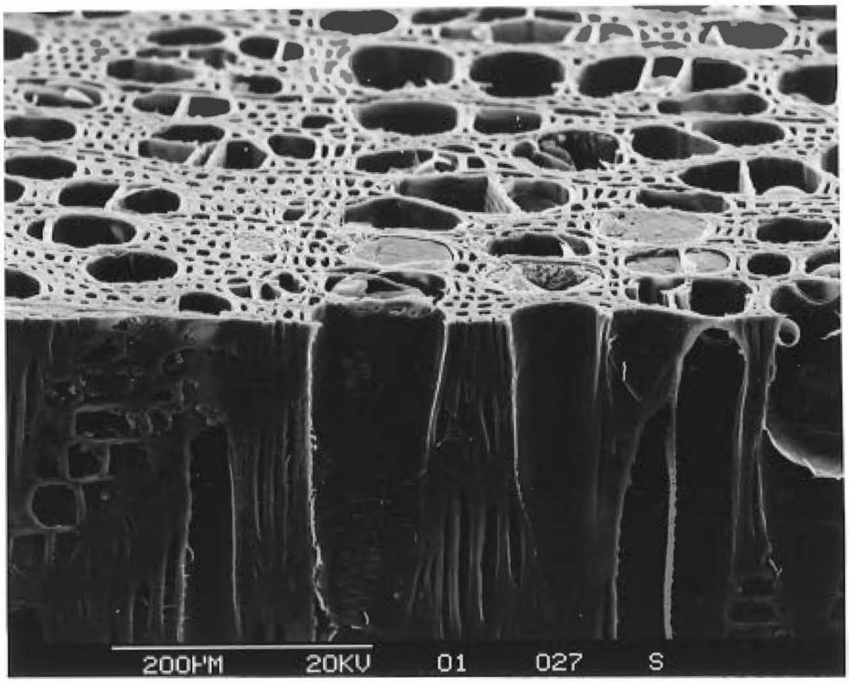


Figure 7.02 SEM; Cross section of N.fusca with most vessels occluded with tyloses in control

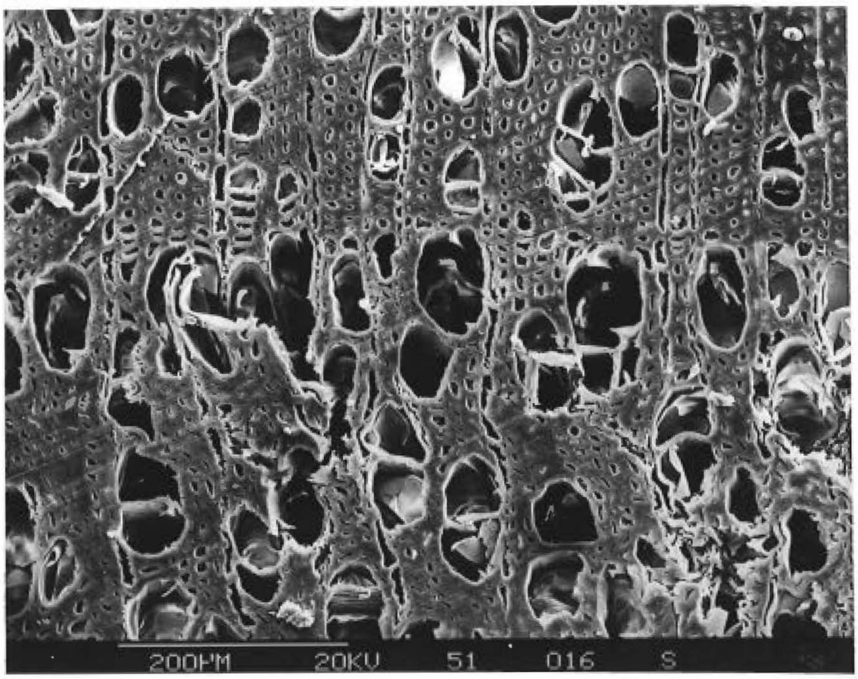


Figure 7.03 SEM; Cross section of N.fusca with severely damaged earlywood vessels and collapsed vessel walls; effects of rolling at a moisture content above 100%, 10% compression level with large rollers (206.8 mm diameter) and at a feed speed of 1000 mm/s

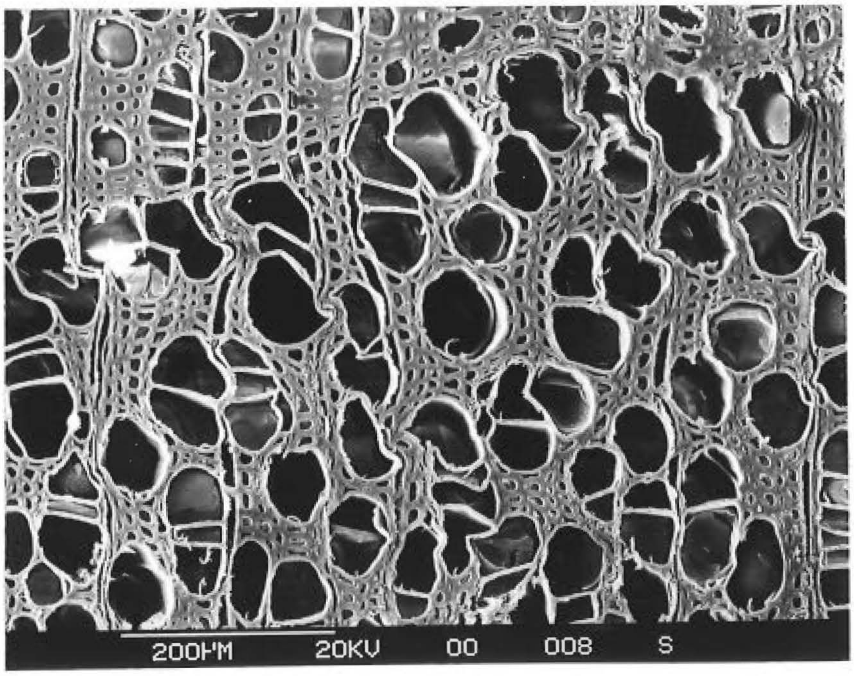


Figure 7.04 SEM; Cross section of N.fusca with deformed vessel walls and ruptured tyloses; effects of rolling at moisture contents around 60%, (rolling conditions as in 7.03)

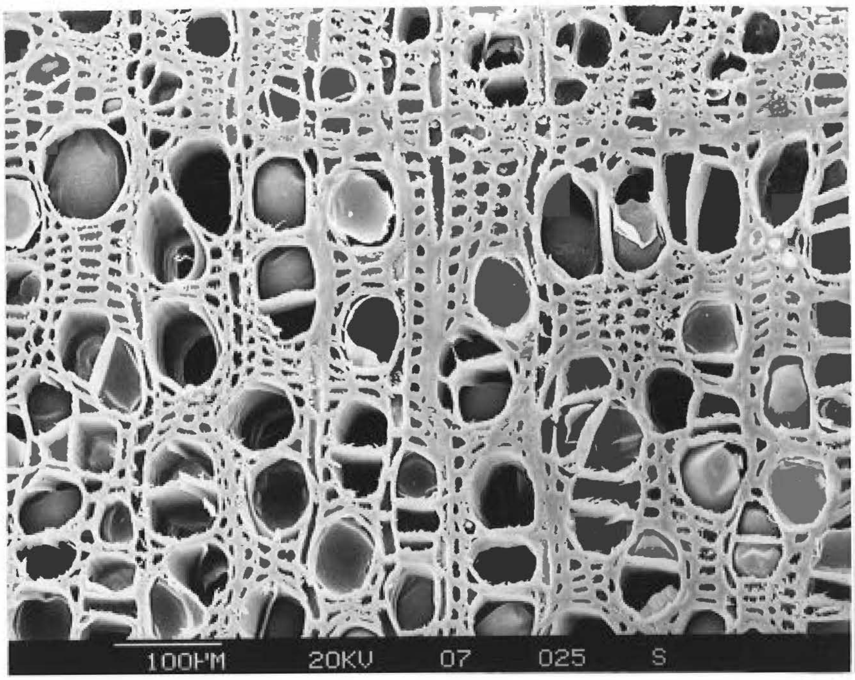


Figure 7.05 SEM; Cross section of N.fusca with limited damage to earlywood vessels; effects of rolling at a moisture content around 20%, (rolling conditions as in 7.03)

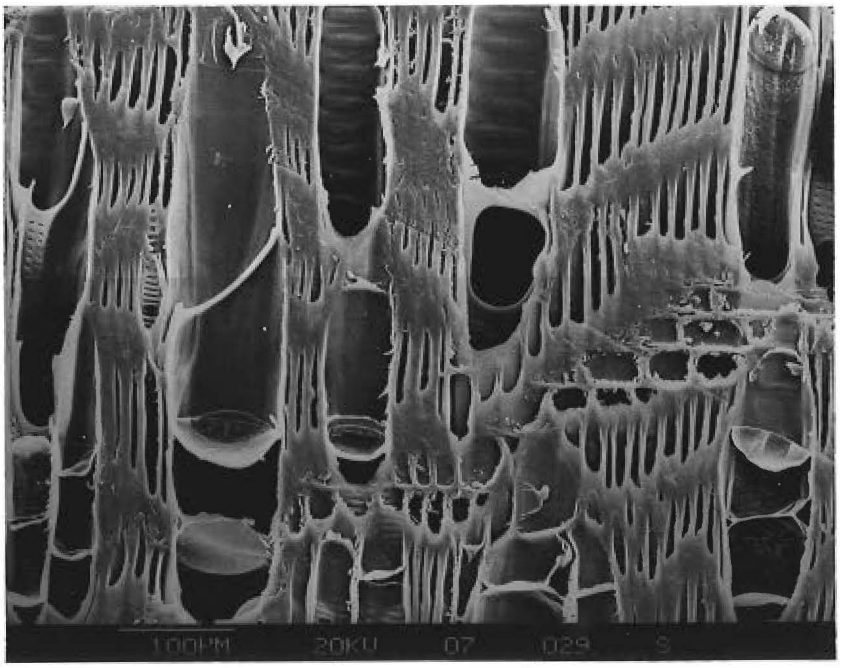


Figure 7.06 SEM; Radial section of a control of N.fusca showing intact tyloses in vessels

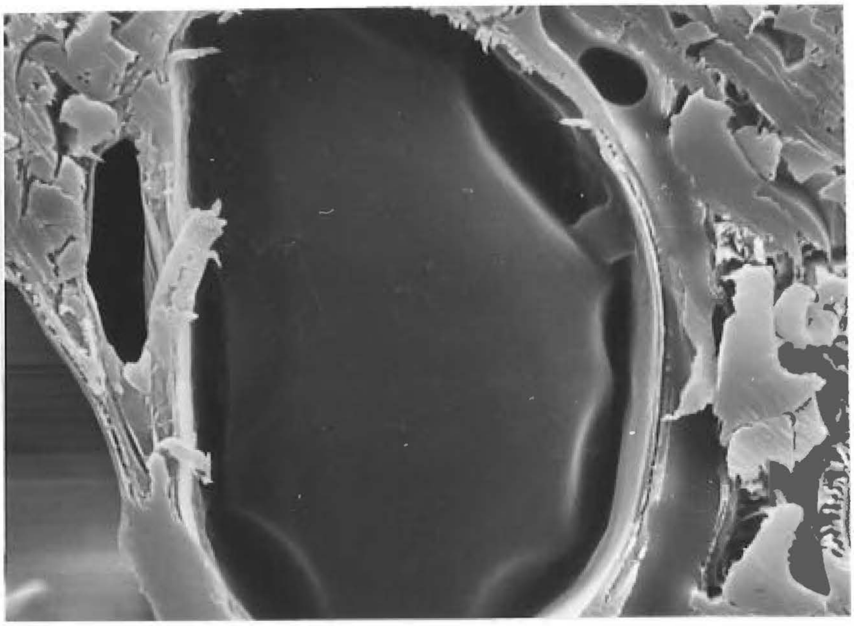


Figure 7.07 SEM; Cross section of N.fusca with intact tyloses within a vessel of a control

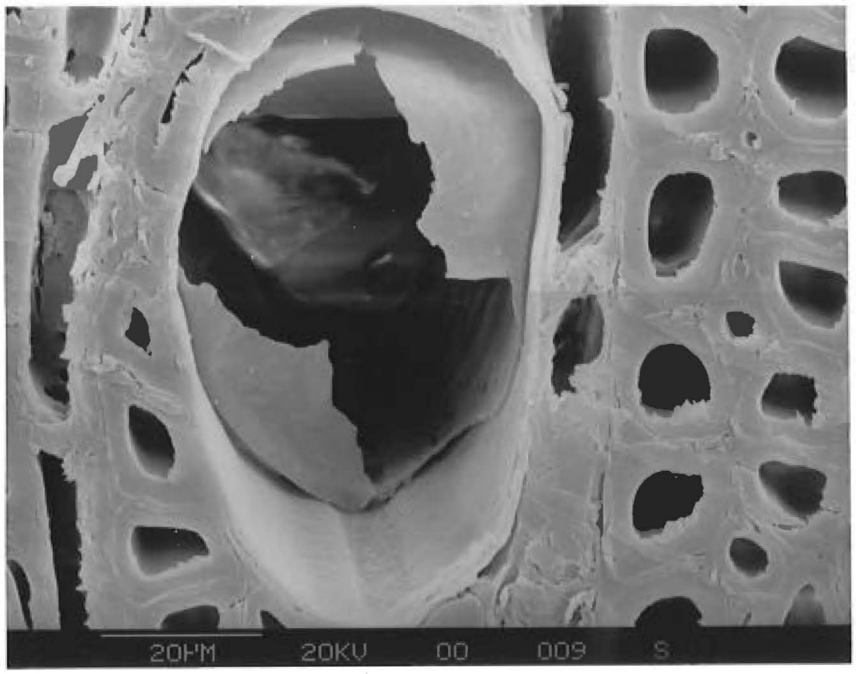


Figure 7.08 SEM; Cross section of N.fusca showing a ruptured tyloses after compression rolling at 60% moisture content (rolling conditions in Figures 7.03)

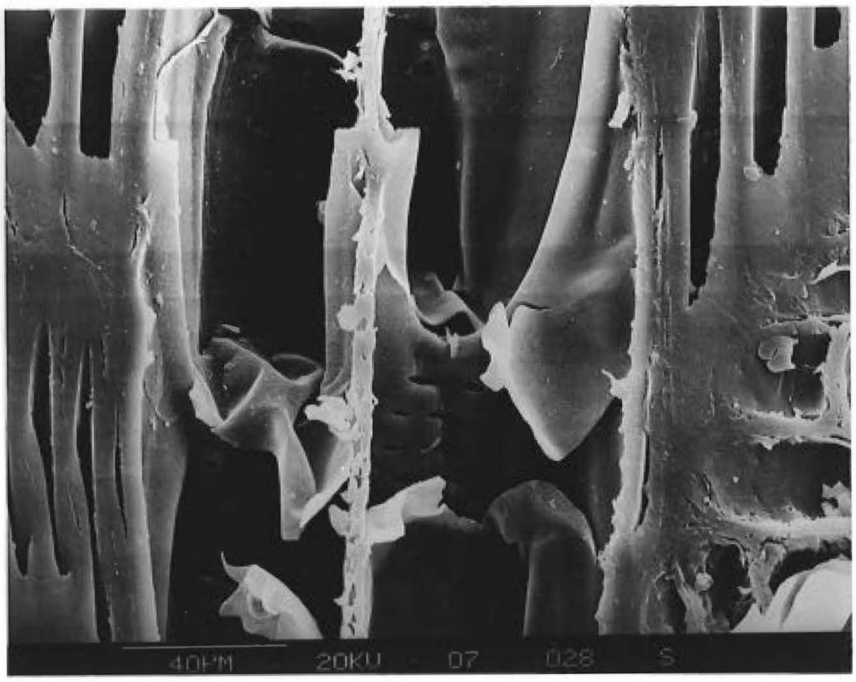


Figure 7.09 SEM; Radial section of N.fusca with ruptured tyloses within a deformed vessel after rolling at 60% moisture content (rolling conditions as in Figure 7.03)

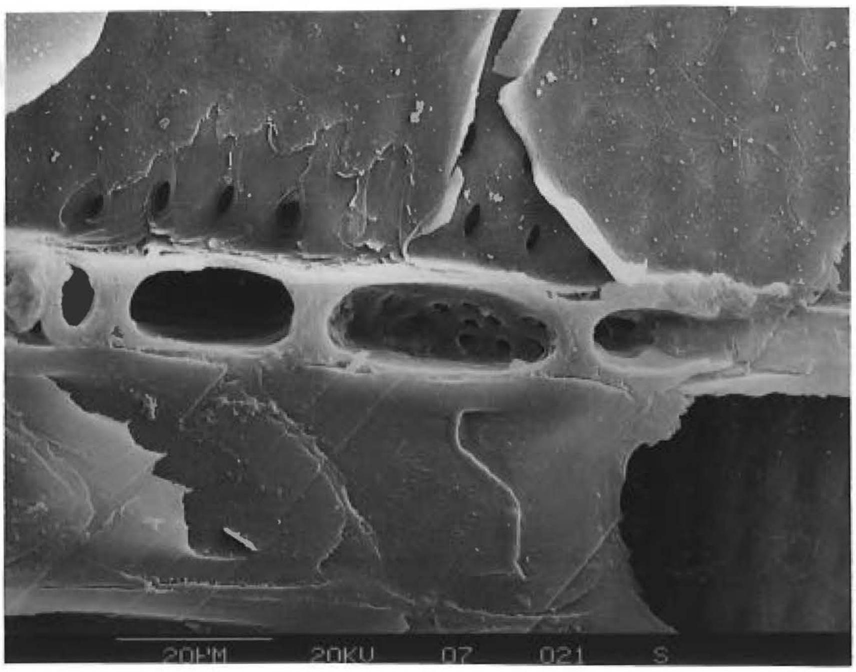


Figure 7.10 SEM; Tangential section of N.fusca showing intact ray parenchyma and terminal ray/ vessel pits in a control

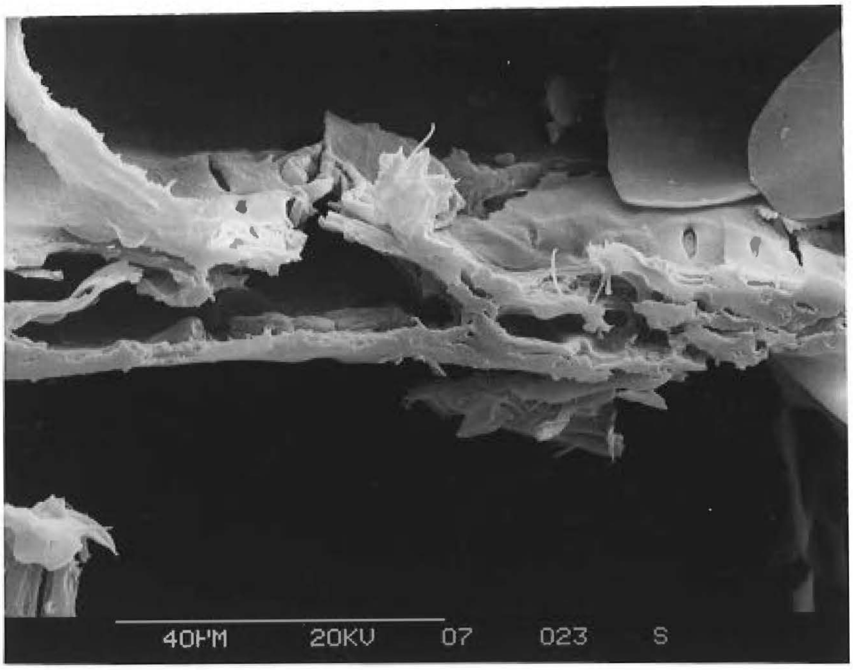


Figure 7.11 SEM; Tangential section of N.fusca with ruptured ray parenchyma wall after rolling at a moisture content above 100% (rolling conditions as in Figure 7.03)

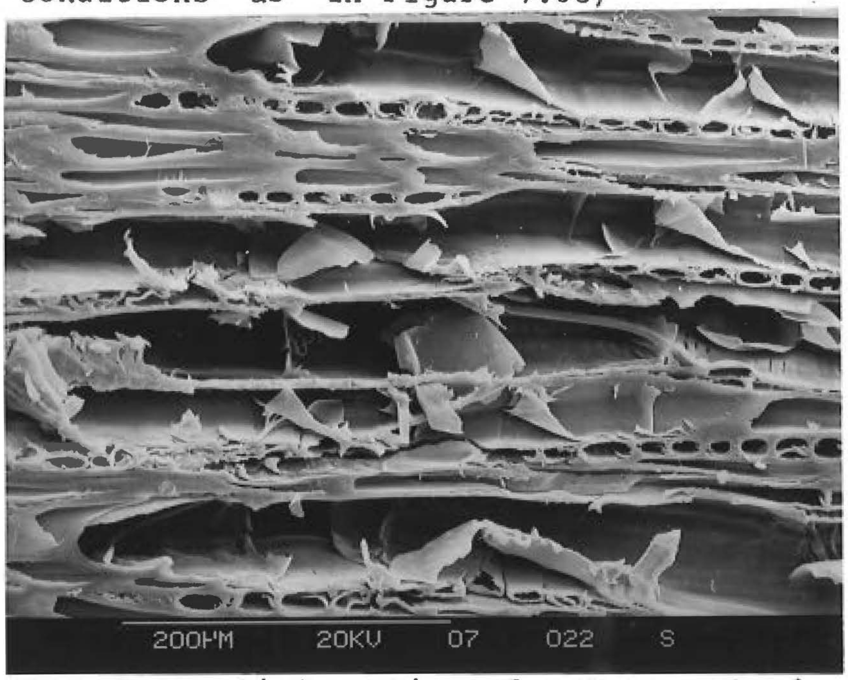


Figure 7.12 SEM; Tangential section of N.fusca showing substantial damage to ray and vessel tissue in a board rolled at a moisture content above 100% (rolling conditions as in conditions as in Figure 7.03)

The fracture pattern can be interpreted as follows: the displacement of fluid mainly through the vessel elements leads to an increase in circumferential stress ($\sigma = (r \times p)/t$) on radial and tangential vessel walls, and in longitudinal stress ($\sigma = (r \times p)/2t$) acting on perforation plates and occluding tyloses; where "r" is the radius of the vessel element, "p" the internal pressure and "t" the wall thickness of the element under consideration (Gordon, 1978). Pressure relief and hence the direction of flow is a function of the strength of the different cell-envelope components (perforation plates, tyloses and pit membranes) as explained earlier (Ch.6); it is also a function of the applied stress. Some of the circumferential stress will be supported by the vessel walls whereas the longitudinal stress is borne entirely by the cell-envelope component, which is comparatively weak.

The anatomical alterations inflicted by rolling can be summarized as follows:

- There is extensive damage to the vessel tissue, including tyloses, perforation plates and vessel to vessel walls, also,
- occasional damage to vessel-to-ray walls, is mainly concentrated on areas adjacent to the terminal ray cell pitting.
- Overall, damage is more pronounced in earlywood than in latewood; this finding applies in particular to boards rolled at high saturation levels, where

extensive fracture at macroscopic level was noticed (Figures 7.14 - 7.17).

- Damage to the ray parenchyma is limited to zones adjacent to vessels; no fracture in radial ray to ray walls or pit membranes occurs.
- No microstructural damage is noticeable in the fibrewalls, although in highly saturated rolled boards some delamination in the middle lamella between fibre walls and vessel walls occurs.
- Pit membranes in vessel-to-vessel walls and fibre-to-fibre pits often appear damaged, but this observation is also common in samples from unrolled controls and hence attributed to artefacts during drying and preparation.

The experiences regarding level of saturation during rolling are similar to those reported by Haslett (personal communication, 1983), who recorded similar fracture patterns in some of his boards, which were rolled at very high moisture contents. This finding is not documented in any other work, but none of the other species were compression rolled at similar saturation levels of approximately 90% (see Table 2.4 and 2.5).

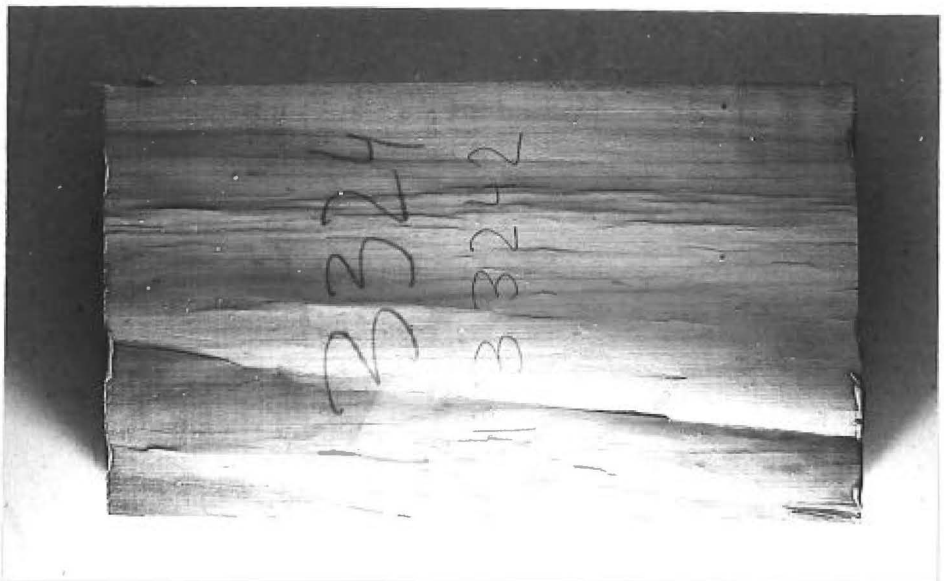


Figure 7.13 0.5 x magnification; View of top surface of sample; delamination in flatsawn board of N.fusca rolled at a moisture content above 100% at 1800 mm/s with the small roller applying a compression of 13%

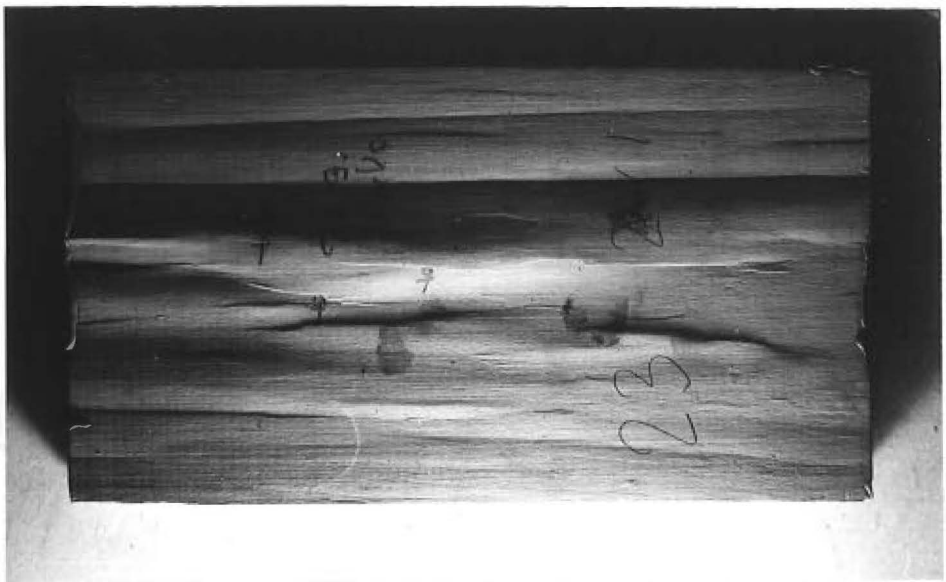


Figure 7.14 0.5 x magnification; View of top surface of sample; damage in flatsawn board of N.fusca rolled at a moisture content above 100%, at 500 mm/s with the large roller size applying a compression of 13%

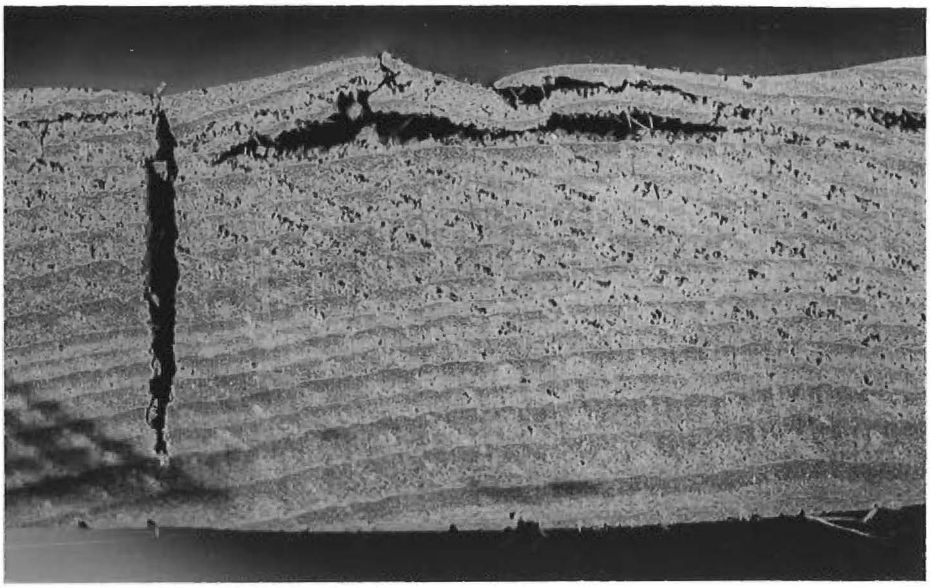


Figure 7.15 4 x magnification; Cross section of a board of N.fusca illustrating the delamination of the top surface after rolling at a moisture content above 100% (rolling conditions as in Figure 7.13)

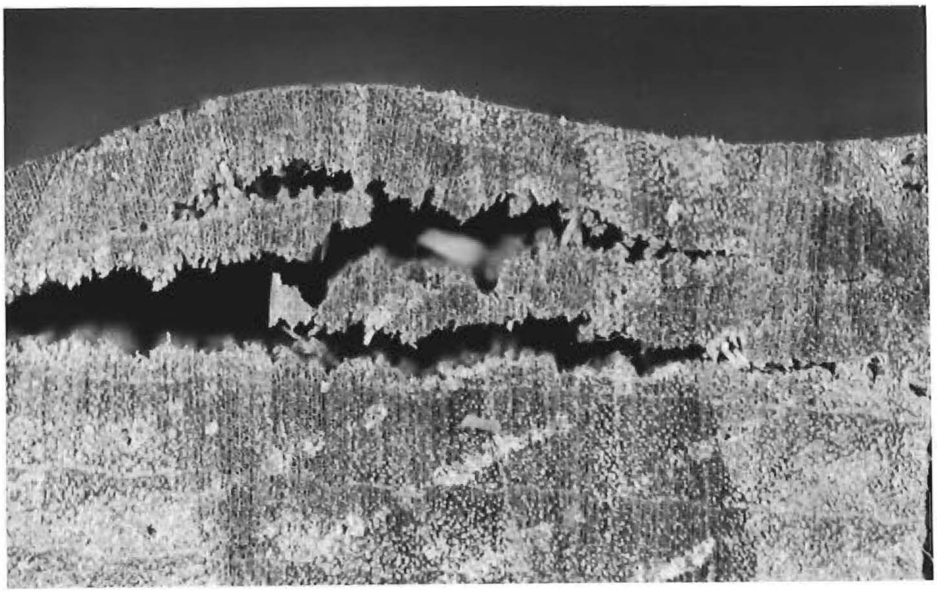


Figure 7.16 8 x magnification; Cross section of N.fusca demonstrating damage concentration in early-wood band of board rolled at a moisture content above 100% (rolling conditions as in Figure 7.13)

7.2 EFFECTS ON THE PERMEABILITY OF NOTHOFAGUS FUSCA

A substantial improvement in preservative uptake and penetration was achieved with rolling. The most important parameters affecting the degree of improvement were compression level and moisture content at the time of rolling. The best results were obtained for a compression level of 13% applied to flatsawn boards at 20% moisture content, which improved preservative uptake by 550%. The increase in uptake can be related to microstructural changes occurring during rolling, primarily affecting vessels and adjacent cells, either paremchymatic or fibrous.

The importance of vessels for preservative treatment of hardwoods, their size and shape, distribution and condition is recognized and described by many authors (Thompson and Koch, 1981; Levy and Greaves, 1978; Teesdale and MacLean, 1918), but has not been mentioned in previous compression rolling studies. The presence of tyloses within vessels is regarded as one important obstacle to treatment, but according to Thompson and Koch (1981) "...in a few species, including American beech and some species of oak and hickory are thin walled and can be ruptured during treatment of the wood, thus permitting penetration..."

In a study of anatomical structure, natural durability and treatability of a Chilean beech (Nothofagus coigüe), Juacida (1978) compares the permeability of sap and heartwood by applying both creosote and water borne preservatives under pressure. He concluded that the extreme difference in treatability (= permeability) between heart- and sapwood is primarily due to the high frequency of tyloses and the presence of extractives (7.3% on an oven dry weight/weight basis) in the heartwood. The penetration of an aqueous solution of Anilin blue (treatment conditions: 60 kPa vacuum, 30 min; 800 kPa pressure, 60 min) showed axial permeability in sapwood 111 times greater than in heartwood, while radial permeability was only 13 times greater and tangential permeability 8 times greater in sapwood.

Similar findings were reported in a study on the transverse permeability of Nothofagus fusca by Kinninmonth (1971 I.), who found that heartwood was completely impermeable under his test conditions (permeability cell with a pressure differential of 600 mm Hg = 80 kPa), although he suggests that some flow might occur at higher pressures. According to the New Zealand Forest Service (1974), heartwood of Nothofagus fusca is categorized as impermeable for pressure treatments with CCA salts, creosote and pentachlorophenol.

Pressure treatments with CCA preservatives applied to Nothofagus fusca in the course of this work confirmed these findings; uptake and penetration in flatsawn and quartersawn controls were very small and irregular ("patchy"), which can be seen in Figures 7.17 and 7.18:

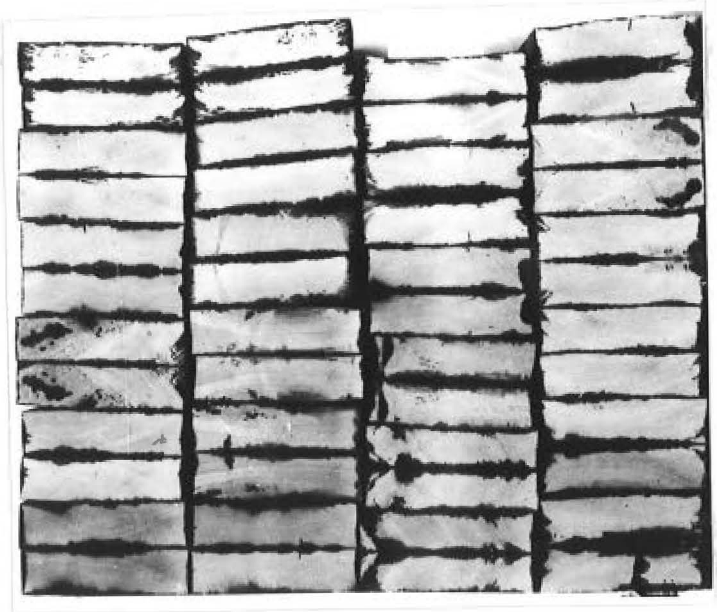


Figure 7.17 Preservative penetration in flatsawn controls of N.fusca (spot-test for presence of CCA with chrome-azurol dye)

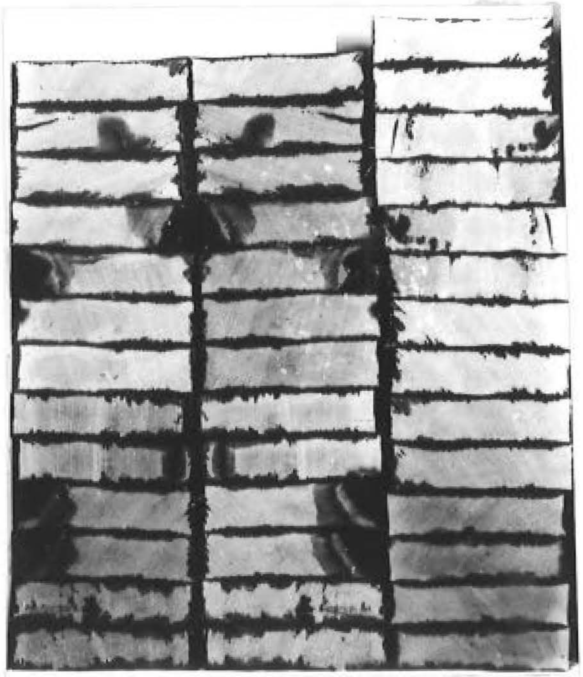
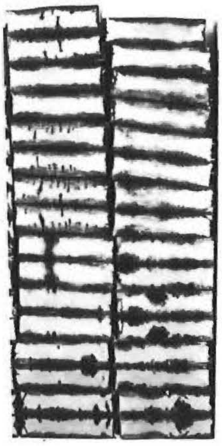


Figure 7.18 Preservative penetration in quartersawn controls of N.fusca (same spot test)

Plate 7.1 Effect of compression rolling with the small roller diameter (50.6 mm) on preservative penetration of <u>N.fusca</u> rolled at initial moisture contents around 120 %

1 = 7 % compression and 800 mm/s feed speed
2 = 7 % compression and 1600 mm/s feed speed
3 = 7 % compression and 2400 mm/s feed speed
4 = 10 % compression and 800 mm/s feed speed
5 = 10 % compression and 1600 mm/s feed speed
6 = 10 % compression and 2400 mm/s feed speed
7 = 13 % compression and 800 mm/s feed speed
8 = 13 % compression and 1600 mm/s feed speed
9 = 13 % compression and 2400 mm/s feed speed



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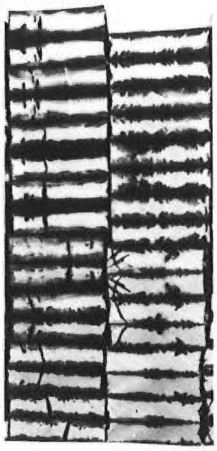

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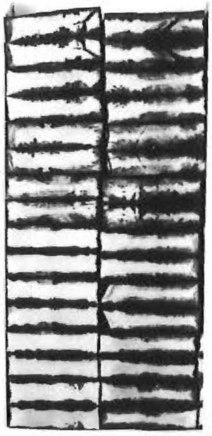

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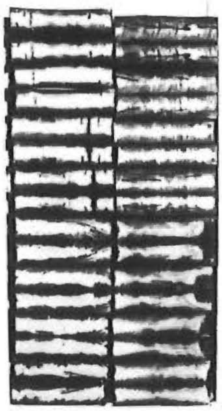

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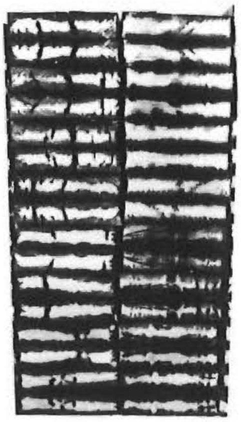

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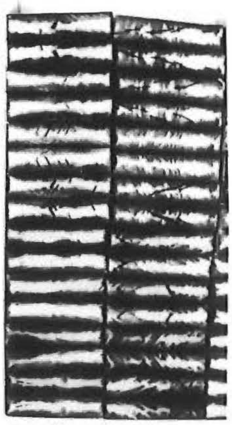

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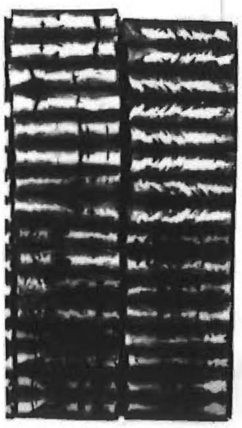

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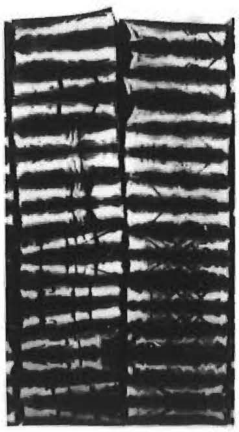

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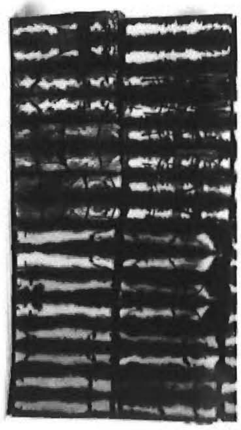

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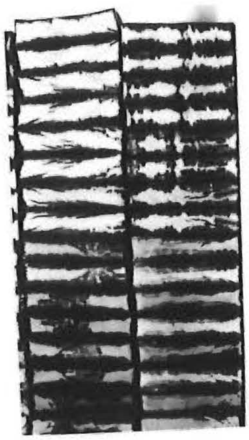
Plate 7.2 Effect of compression rolling with the large roller diameter (206.8 mm) on preservative penetration of N.fusca rolled at initial moisture contents around 120 %

1 = 7 % compression and 800 mm/s feed speed
2 = 7 % compression and 1600 mm/s feed speed
3 = 7 % compression and 2400 mm/s feed speed
4 = 10 % compression and 800 mm/s feed speed
5 = 10 % compression and 1600 mm/s feed speed
6 = 10 % compression and 2400 mm/s feed speed
7 = 13 % compression and 800 mm/s feed speed
8 = 13 % compression and 1600 mm/s feed speed
9 = 13 % compression and 2400 mm/s feed speed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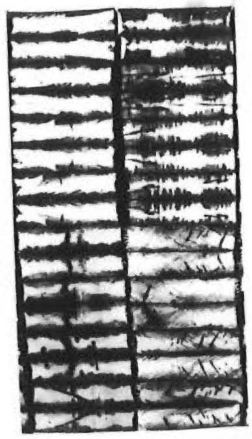
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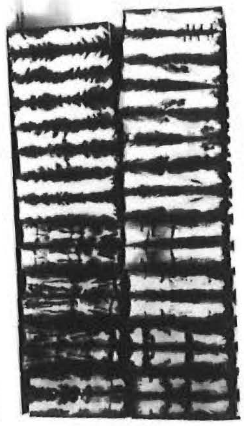
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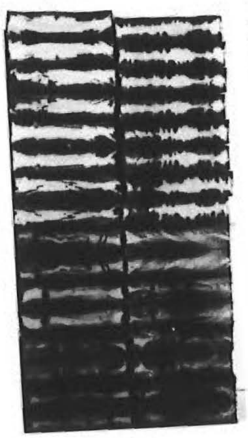
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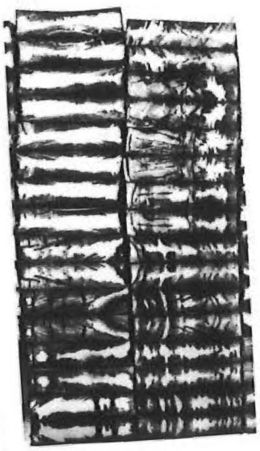
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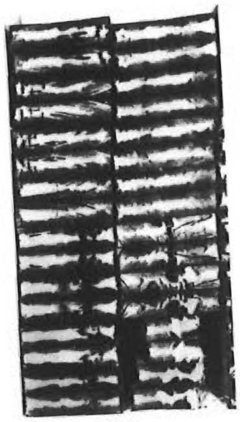
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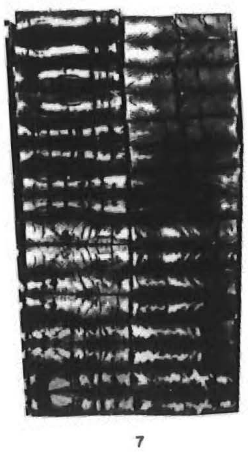
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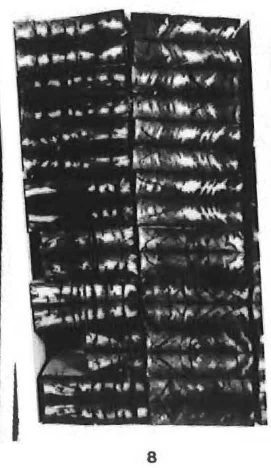
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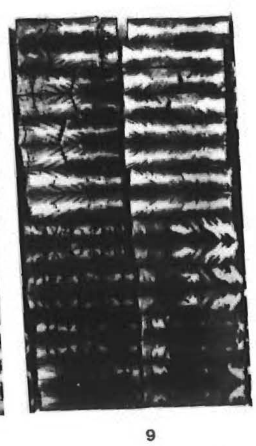
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The improvement in uptake achieved by compression rolling in the main experiment with highly saturated boards is illustrated in Plate 7.1 (numbers 1-9) and 7.2 (1-9). Figures 7.19, 7.20, 7.21 and 7.22 show the pattern of penetration in a control in comparison to a 13% compression-rolled board (rolling with the large roller size). The top and bottom surface of the rolled board have taken up substantial amounts of preservative, while the edges remain unpenetrated. Preservative moves preferentially in the tangential direction. Cracks are present in the board (Figure 7.20) running both in tangential and radial directions, but do not contribute to a further penetration of the preservative; there is no lateral movement of preservative from the immediate vicinity of these cracks.

With an increase in compression level there is an increase in preservative uptake and penetration (Plates 7.1 aand 7.2) and the severity of damage becomes more substantial. The damage was related to the high moisture content during rolling, when the relatively incompressible sap was forced through the vessels and other capillary passages. At all levels of compression the frequency and depth of cracks in the rolled boards increases with an increase in feed speed, underlying the effect of the speed of displacement on the degree of damage. The displacement of sap as induced through rolling is illustrated in Figures 7.23 and 7.24.

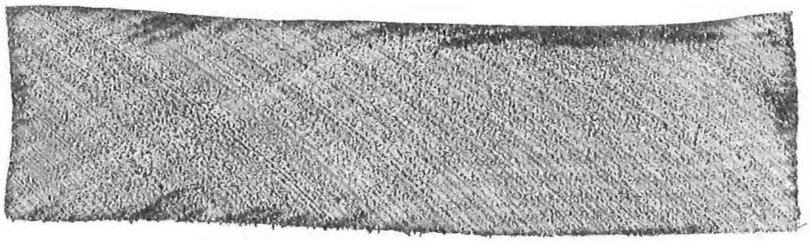


Figure 7.19 1 x magnification; Cross section of a flat-flatsawn control after pressure treatment with negligible tangential penetration.

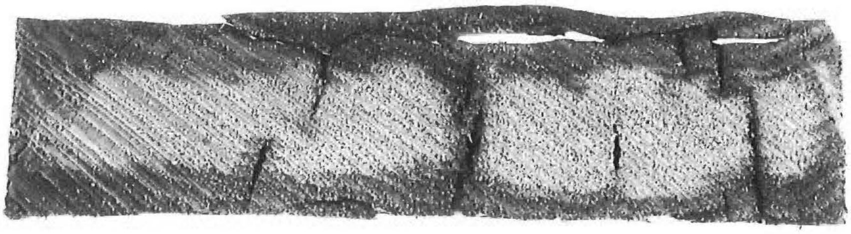


Figure 7.20 1 x magnification; Cross section of a flat-sawn compression rolled board (at moisture content above 100%, 13% compression, large rollers and 1000 mm/s feed speed) after pressure treatment; note that penetration is limited to the top and bottom faces and no penetration occurs laterally from cracks

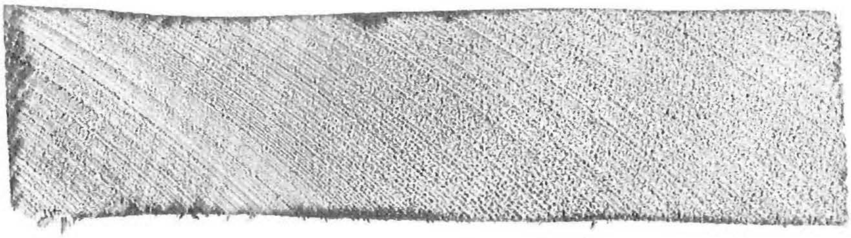


Figure 7.21 1 x magnification; Cross section of a quartersawn control after pressure treatment with negligible tangential penetration.

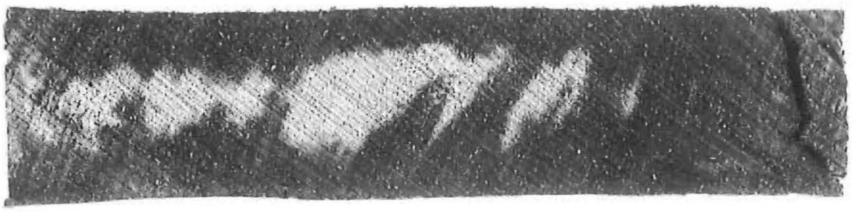


Figure 7.22 1 x magnification; Cross section of a quarsawn, compression rolled board (at moisture content above 100%) after pressure treatment (rolling conditions as in Figure 7.20)

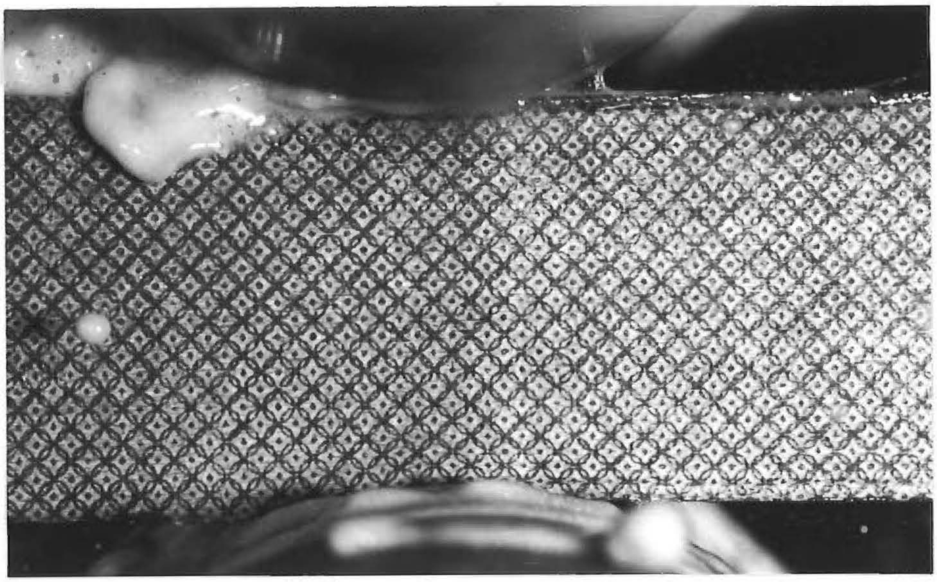


Figure 7.23 Board at moisture content of 120% during compression rolling at 1000 mm/s and 10% compression showing the dynamic displacement of sap.

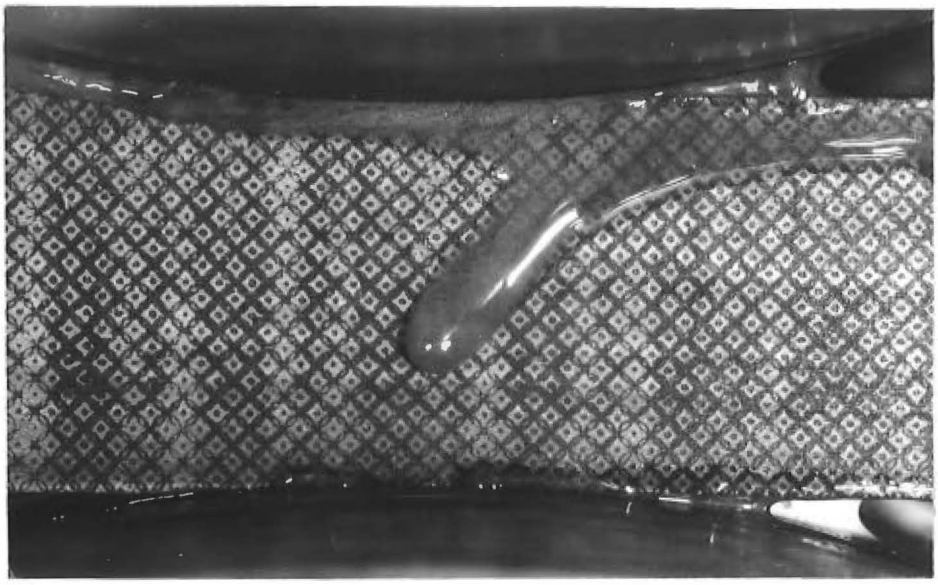


Figure 7.24 Board at a moisture content of 120% during compression rolling at 500 mm/s and 7% compression with sap displaced from the top surface

The depth of deformation as determined by the deformed circles on the edges of the boards generally coincided with the mean depth of preservative penetration, although there were variations in penetration across the width of the board. Not only was penetration limited to the two faces of the boards, but it primarily followed earlywood bands; latewood was not as easily penetrated.

The effects of rolling highly saturated boards of *Nothofagus fusca* on permeability can hence be summarized as follows:

- Substantial improvement in preservative uptake and penetration for all rolling related treatment factors.
- Improvement mainly in axial and tangential permeability
- Penetration primarily restricted to earlywood and only limited and irregular in latewood bands. The deformation as revealed by the grid circles is also unhomogenous, suggesting that earlywood is more highly deformed and weakened - and so accessible to preservative penetration.
- Penetration of ray parenchyma restricted to zones adjacent to vessels.
- Penetration of fibres without visible damage to fibre pits.

These conclusions were also valid for rolling red beech at moisture contents of 60% and below. There is an additional benefit in that there was no evidence of internal cracks or similar damage as occurred when the moisture content approached saturation (Figures 7.25, 7.26 and 7.27).

A more uniform penetration pattern was observed in both flatsawn and quartersawn boards; nonetheless the main direction of CCA penetration is tangential and axial, with preservative located preferentially in the earlywood tissue. The comparison between unrolled controls against replicates rolled at 60% moisture content, subjected to a 10% compression with the large roller size and at a feed speed of 500 mm/s is illustrated in Figure 7.27. Figure 7.28 shows the variation in axial permeability in earlywood and latewood regions.

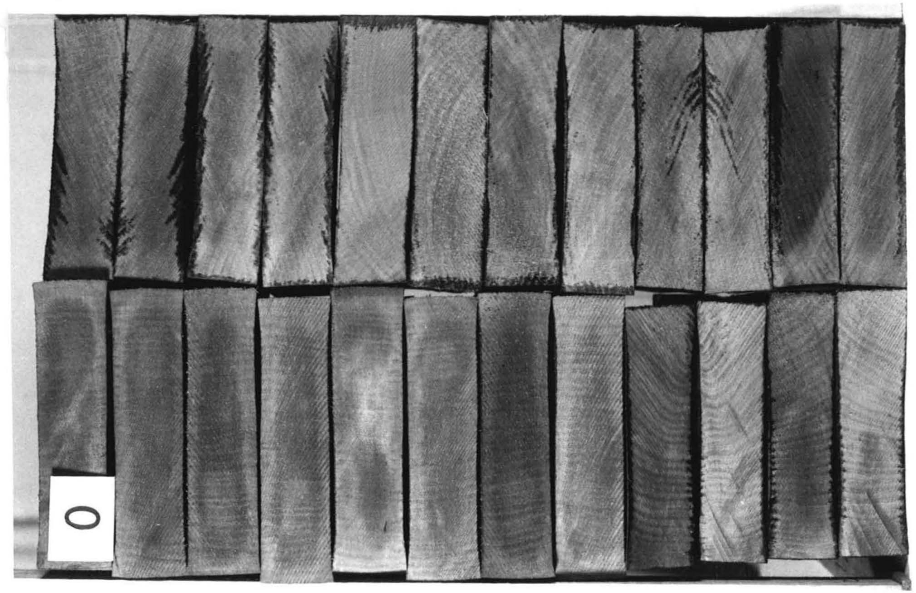


Figure 7.25 Cross sections of controls of N.fusca after preservative treatment

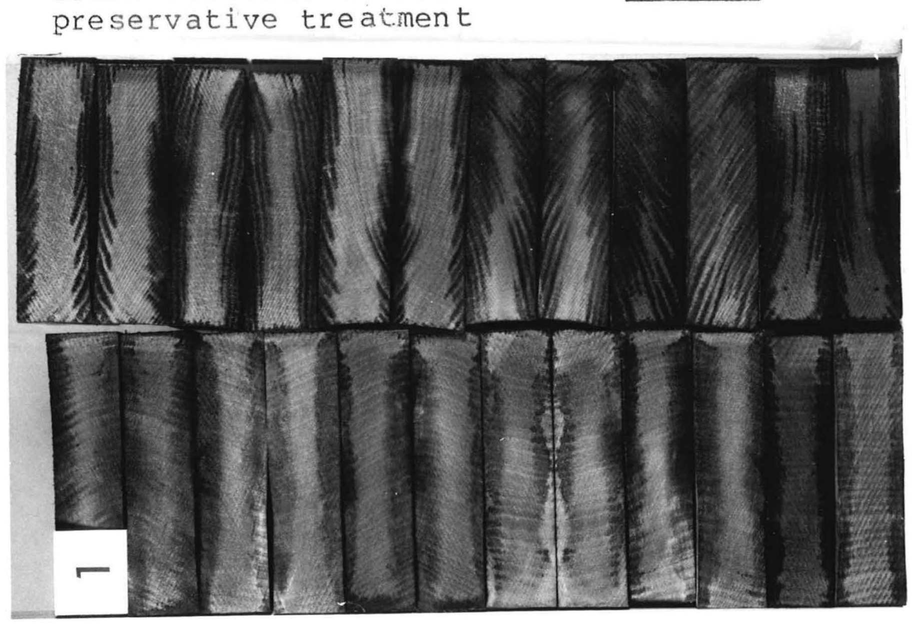
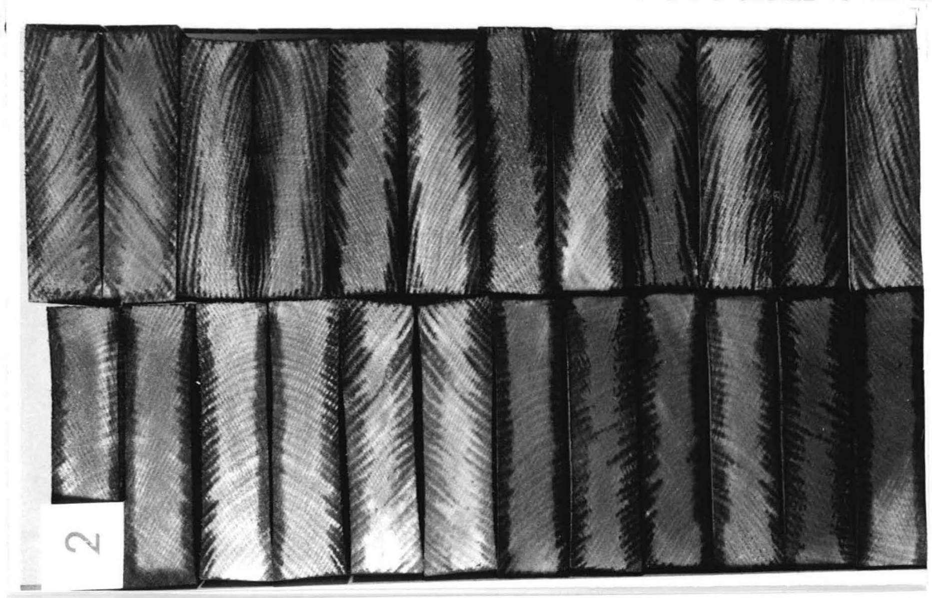
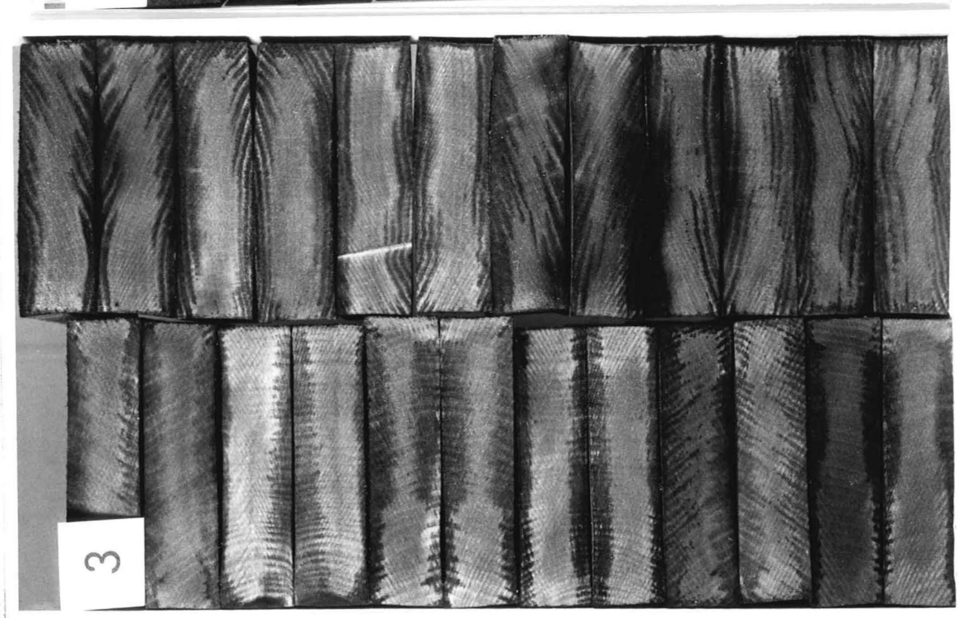
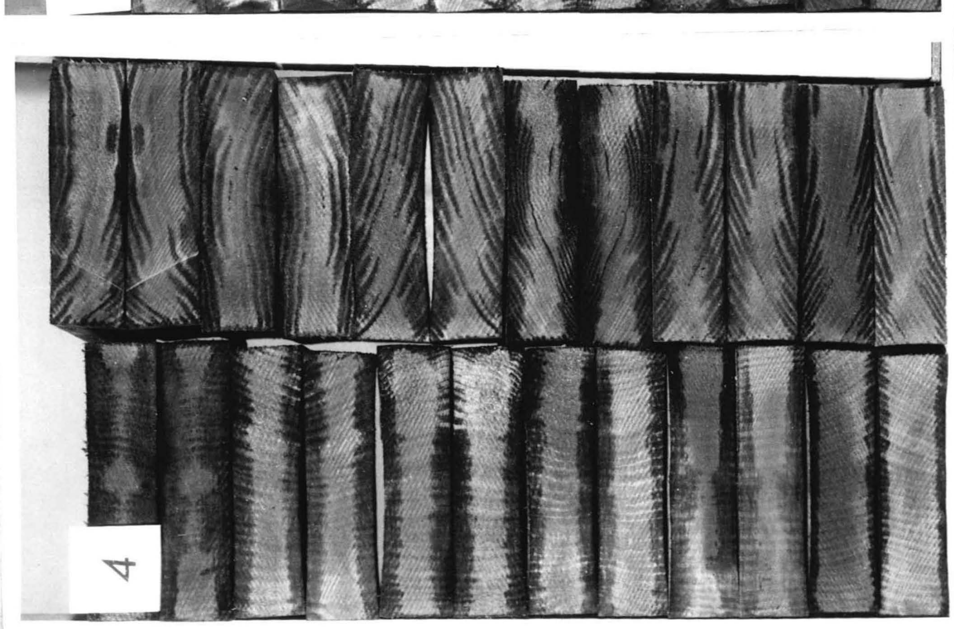


Figure 7.2







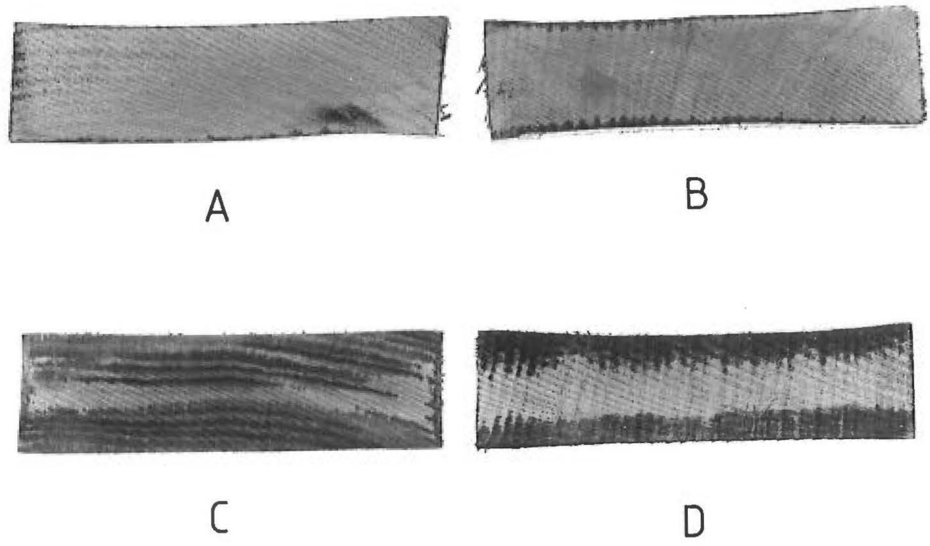


Figure 7.27 Comparison between controls and compression rolled and preservative treated boards of N.fusca (rolling at 60% moisture content) (A,B = controls;C,D = rolled boards at level 2 according to Figure 7.26)

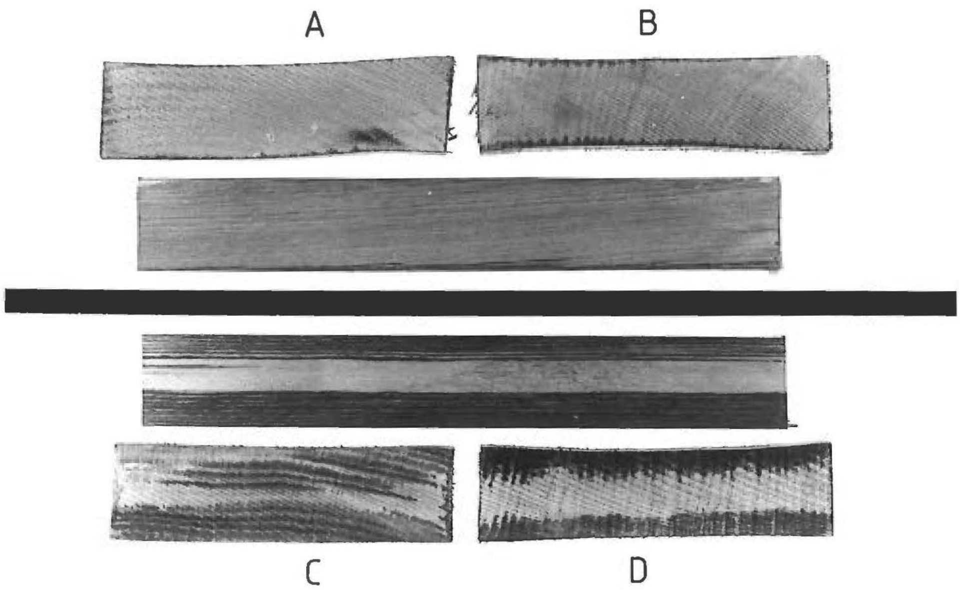


Figure 7.28 Axial and transverse preservative penetration pattern in cross sections of rolled rolled N.fusca compared with controls (Conditions and labelling as in Figure 7.27)

Microscopic examination of the penetrated areas gave further evidence regarding the distribution of preservative within the different cell elements. Most was found in vessels, terminal ray parenchyma and occasionally in the fibres (Figures 7.29, 7.30, 7.31 and 7.32). It also becomes clear that radial ray to ray cell walls are not damaged by the rolling process, since CCA penetration of the rays does not occur radially (Figure 7.32), but is limited to the terminal ray cells. Thus pathways for preservative penetration coincide with those "opened up" by compression rolling.

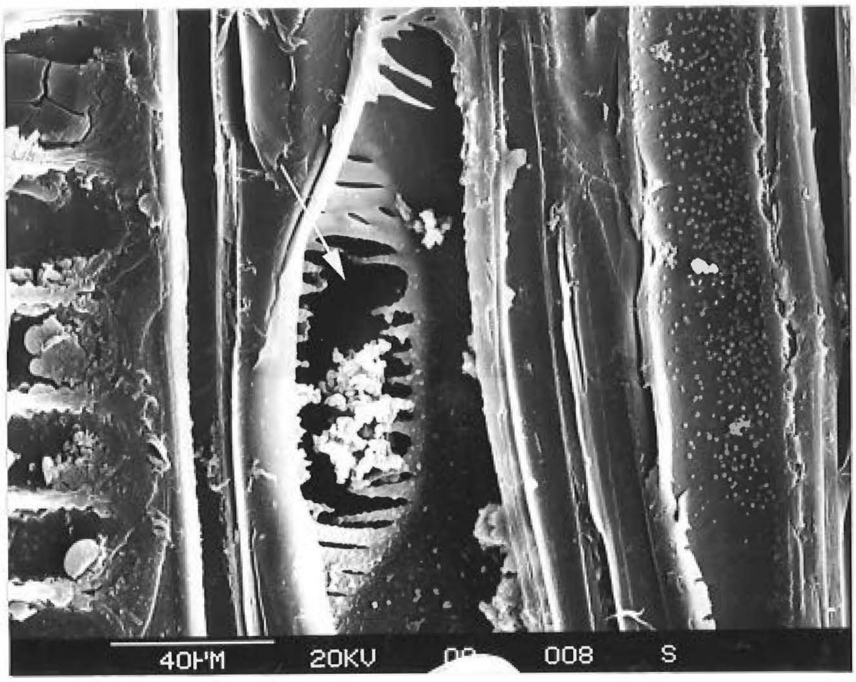


Figure 7.29 SEM; Radial section of N.fusca after rolling and preservative treatment; the arrow marks a damaged perforation plate with CCA particles (rolling conditions as in 7.26, level 2)

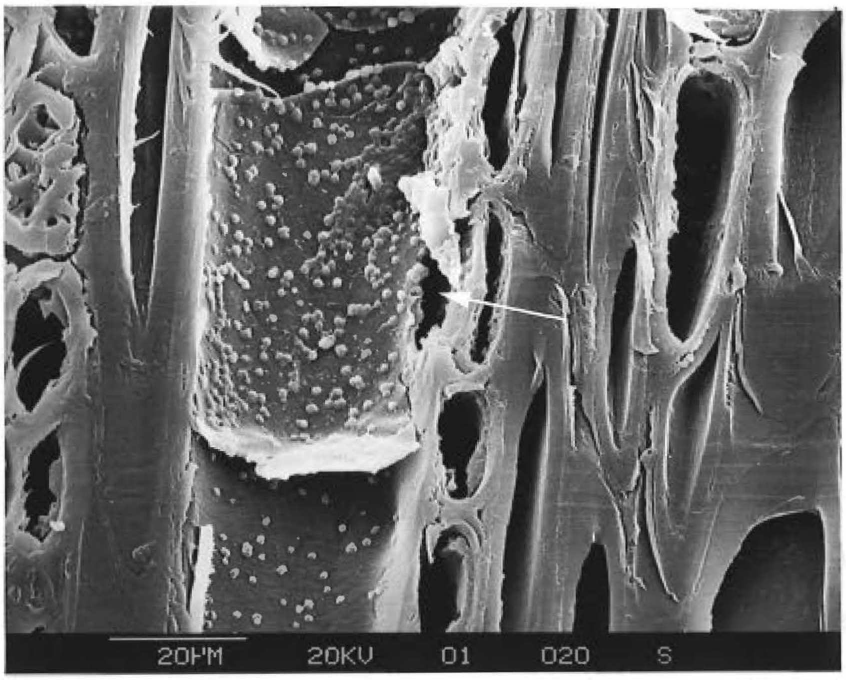


Figure 7.30 SEM; Tangential section of N.fusca after rolling and preservative treatment; the arrow marks a damaged tyloses and collapsed ray-vessel wall (rolling conditions as in 7.26, level 2)

Figure 7.31 240 x magnification, Light microscope (LM); radial section of N.fusca from the center of a rolled and preservative treated board showing unpenetrated ray parenchyma (rolling conditions as in 7.26, level 2)

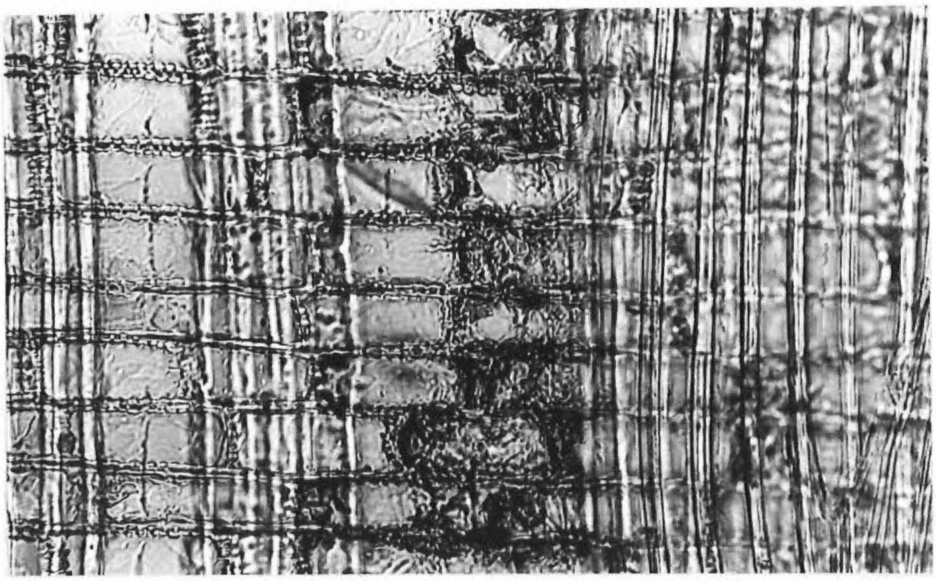


Figure 7.32 240 x magnification, LM; radial section of N.fusca from the face of a rolled and preservative treated board showing penetration of the rays. Radial penetration through the rays is blocked (rolling conditions as in 7.26, level 2)

7.3 EFFECTS ON THE DIFFUSIVITY OF NOTHOFAGUS FUSCA

A statistically significant improvement in drying rate was recorded between rolled and unrolled boards at high saturation levels. However the actual reduction in drying time was not great. Slight increases in drying slope were noticeable with higher compression levels, which is primarily attributed to the substantial damage present in the boards increasing the total surface area for evaporation (Figures 7.33 and 7.34). Reductions in drying time were not achieved in subsequent rolling experiments of boards compressed at moisture contents below 60%, in which no cracks were formed by rolling (Graph 7.1).

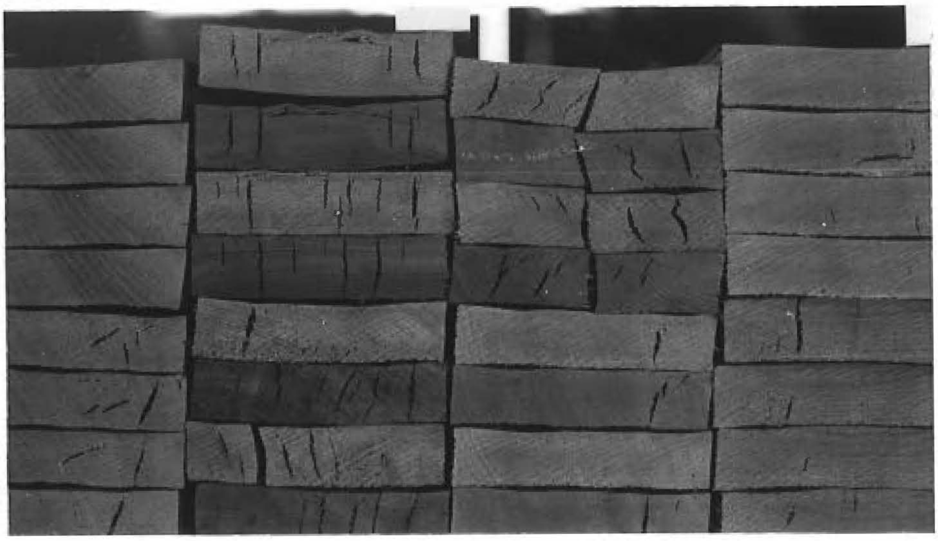


Figure 7.33 0.5 x magnification; Cross sections of dried boards of N.fusca after compression rolling at a moisture content above 100% (large roller size, 13% compression level and 1000 mm/s)

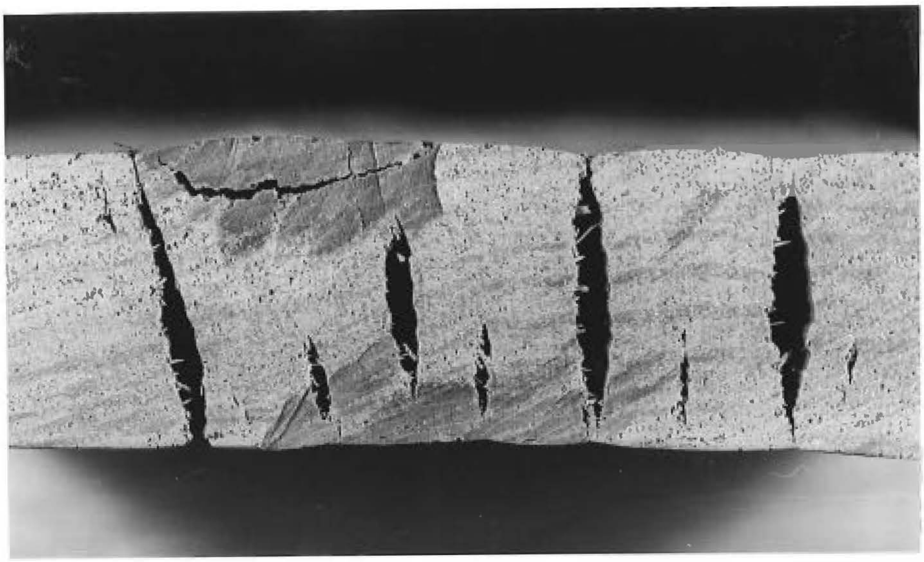


Figure 7.34 2 x magnification ; Cross section of air dried flatsawn board of N.fusca after compression rolling at a moisture content of 122% (large roller size, 13% compression level and 1000 mm/s); radial splits represent rolling related damage

A common observation for all treatments tested and at both moisture content levels was that flatsawn boards showed steeper drying slopes than similarly treated quartersawn boards (Graphs 5.4 and 7.1). These findings agree with Kinninmonth (1973), who conducted a detailed study on the drying behaviour of Nothofagus fusca heartwood and sapwood. His figures indicate that radial diffusion is 39% greater than tangential diffusion in sapwood and 30% faster in heartwood. It appears that ray parenchyma play a major role in drying, despite containing considerable quantities of extractives. The importance of ray cell contents on radial diffusivity in heartwood will be discussed further in chapter 7.5.

Extensive examination and comparison of the drying curves of individual boards of Nothofagus fusca heartwood led to the conclusion that compression rolling does not affect the main pathways through which diffusional drying occurs. There was no indication of microstructural damage which might affect the radial permeability of the ray tissue. Pathways "opened up" by the rolling process (see section 7.1) do not contribute substantially to drying either by water vapor diffusion or by bound water diffusion, except when macroscopic damage (cracks and splits) is caused at very high moisture contents (as in Figure 7.33 and 7.34). The reason for this apparent contrast to those findings of the author on the effects of compression rolling on permeabilty (chapter 7.2) is attributed to the irregularity of damage distribution. Apparently the rolling process only increases permeability of some parts, mainly earlywood bands, without creating continuous pathways for water vapor diffusion, which represents an important component of the diffusional drying.

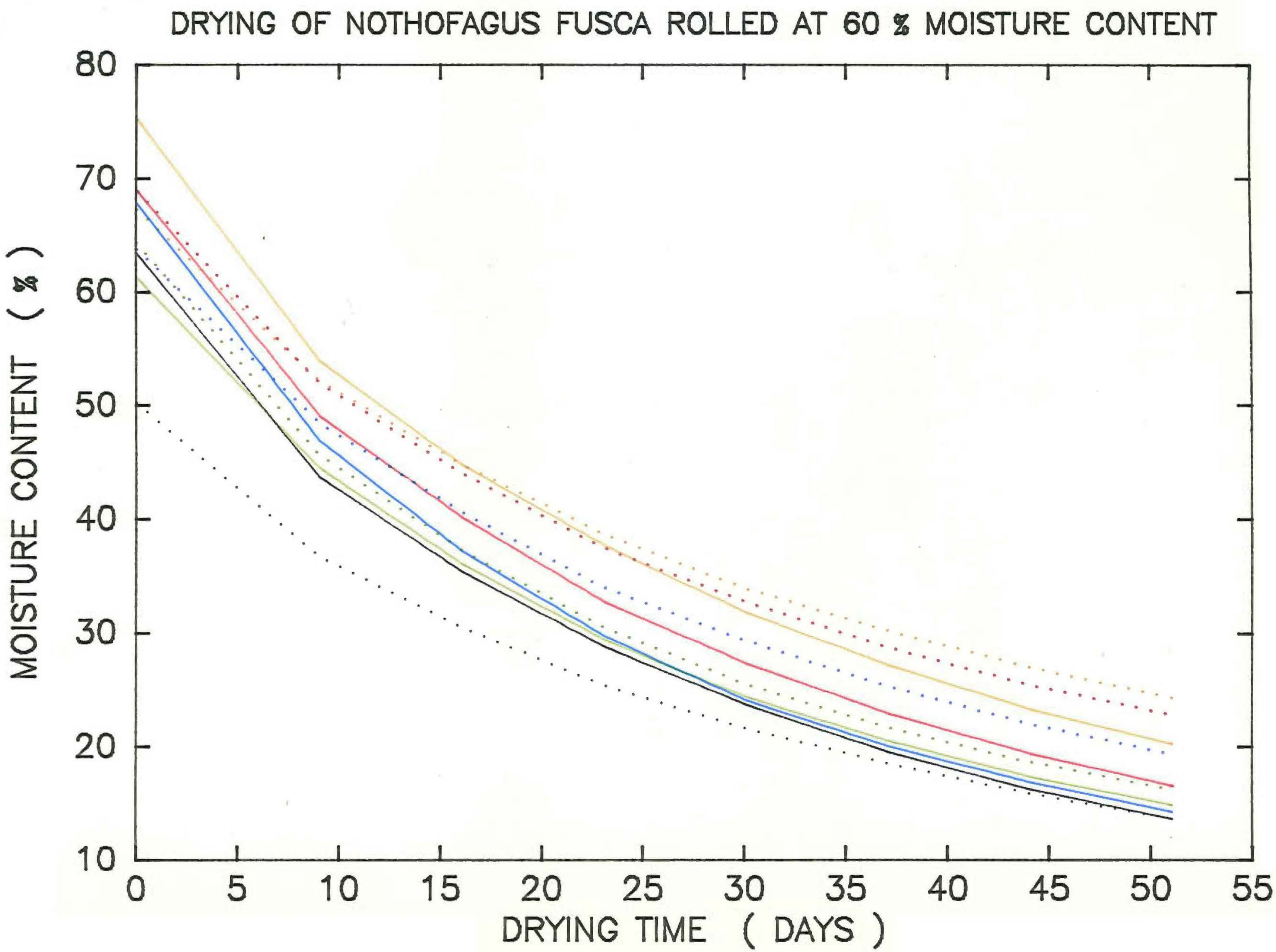
Graph 7.1 Drying of <u>Nothofagus fusca</u> rolled at 60% moisture content

(Each drying curve represents the mean of 4 replicates)

Continuous lines: Flatsawn boards
Dotted lines: Quartersawn boards

Black: Controls
Gold : 500 mm/s Feed speed (nominal)
Blue : 1000 mm/s Feed speed (nominal)
Green: 2000 mm/s Feed speed (nominal)
Red : 3000 mm/s Feed speed (nominal)

Rolling conditions; Roller diameter: 206.8 mm
Compression level : 10 %


DRYING OF NOTHOFAGUS FUSCA ROLLED AT 60 % MOISTURE CONTENT
MOISTURE CONTENT (%)
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
50
55
DRYING TIME (DAYS)

7.4 EFFECTS OF AN ADDITIONAL HOT SOAKING TREATMENT ON THE ANATOMY OF *NOTHOFAGUS FUSCA*

Hot water soaking at high moisture contents has a similar effect on the ultrastructure of *Nothofagus fusca* as the 3 hour steaming pretreatment at 100 ^{o}C of Kininmonth (1971). Comparisons between unsoaked controls and soaked boards under the scanning electron microscope showed clear differences between the structure of the extractives present principally in the ray parenchyma (Figures 7.35, 7.36, 7.37 and 7.38). In the course of the pretreatment a relocation and partial extraction of these extractives occurs uncovering the radial and tangential ray cellwalls, clearing pit membranes and micropores (Figure 7.39).

Splits in the fibre walls were present, occasionally propagating from a fibre / fibre pit into the wall (Figure 7.40 and Figure 7.41). Vessels were not affected by the hot water pretreatment and damage to tyloses was very rare (Figure 7.42).

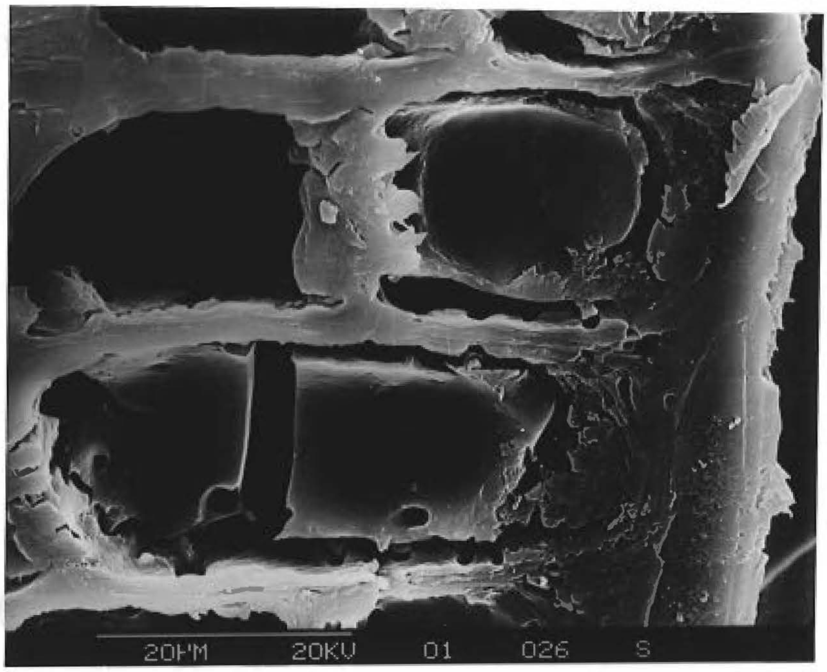


Figure 7.35 SEM; Radial section of <u>N.fusca</u> control; encrustations in ray parenchyma forming solid blocks.

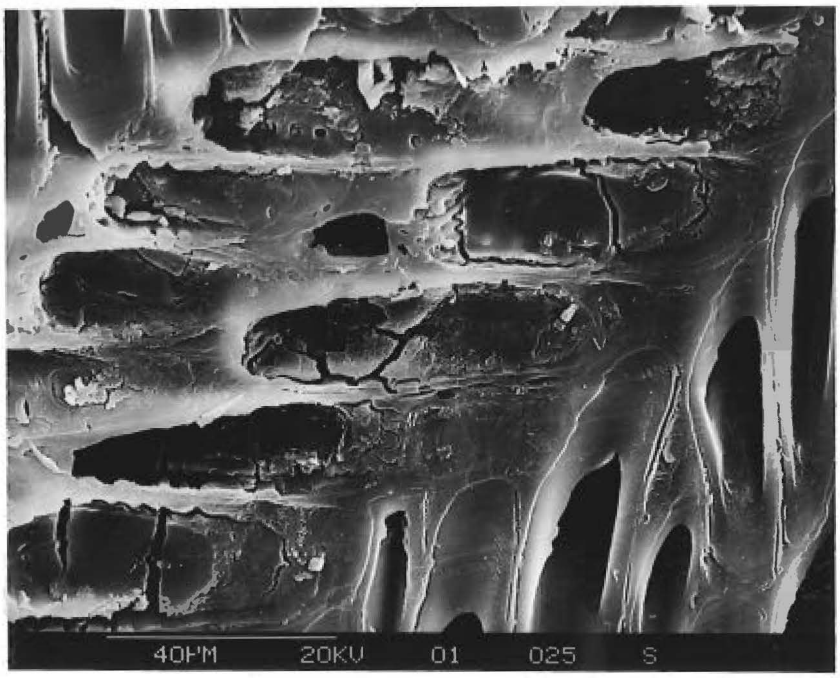


Figure 7.36 SEM; Radial section of <u>N.fusca</u> control; phenolics in ray parenchyma occluding most of the lumen.

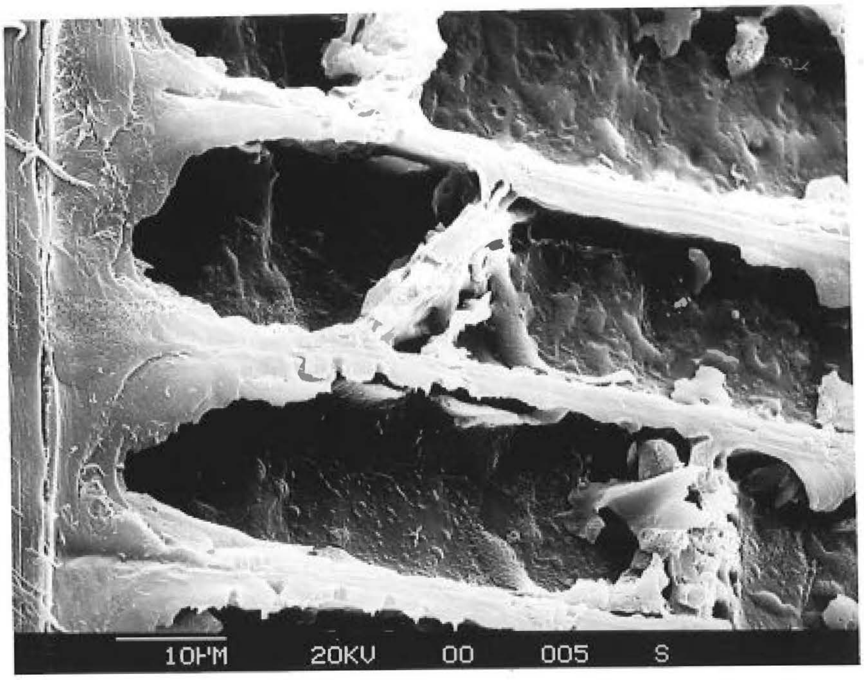


Figure 7.37 SEM; Radial section of N.fusca after hot soaking treatment; some of the extractives have been removed from the wood into the surrounding water.

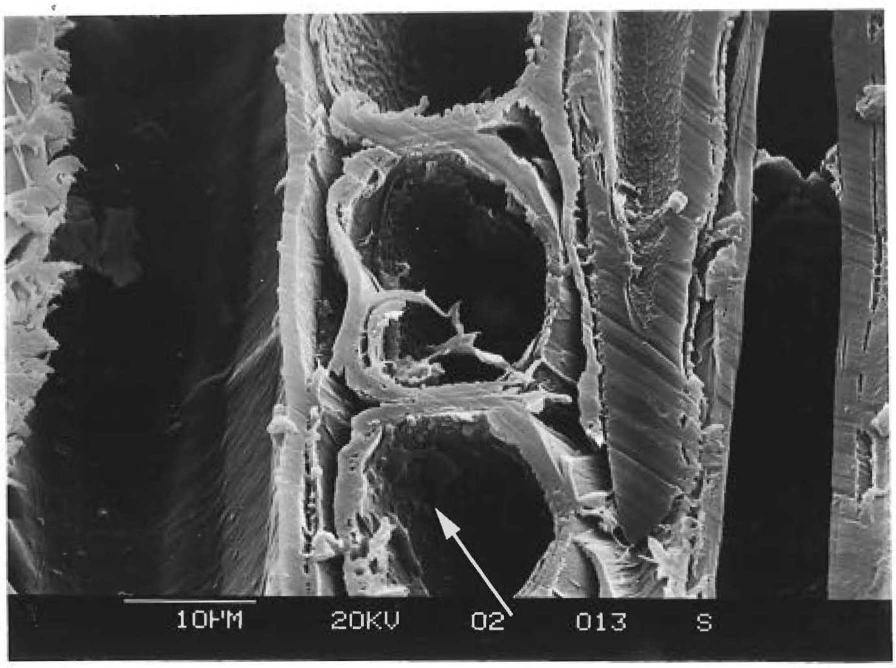


Figure 7.38 SEM; Tangential section of N.fusca after hot soaking treatment with remains of extracted phenolics in the ray; the arrow marks coagulation on the inner ray-cell wall.

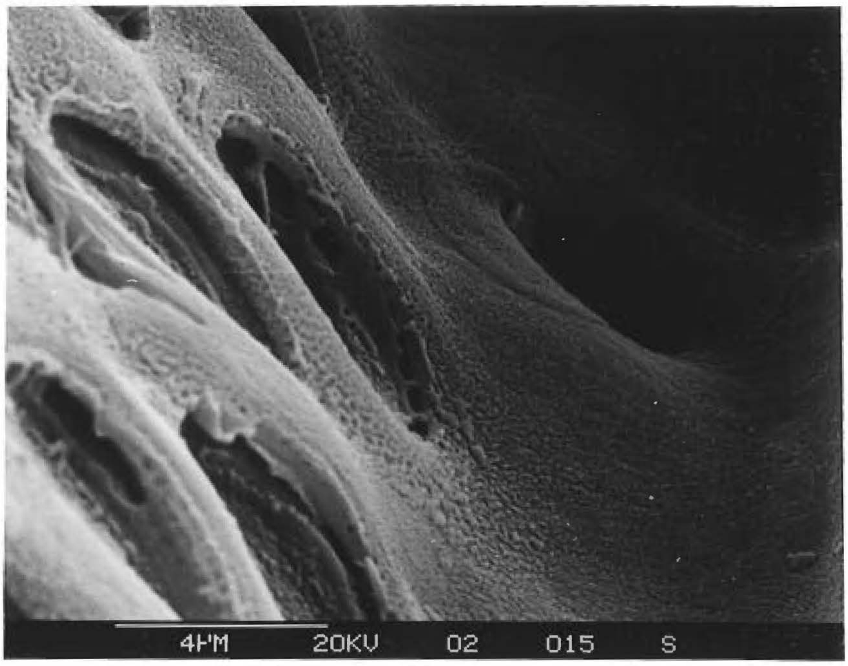


Figure 7.39 SEM; Radial/tangential section of hot water soaked <u>N.fusca</u>; terminal ray-to-vessel pit showing discontinuity in film of phenolics lining the vessel wall.

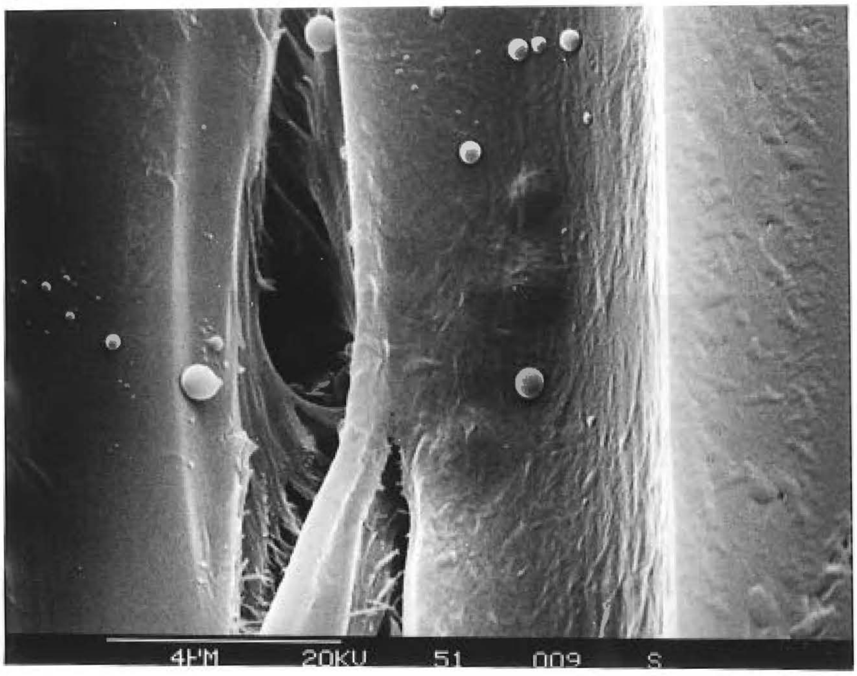


Figure 7.40 SEM; Radial section of hot water soaked <u>N. fusca</u>; fibre pit with split propagating axially into the wall.

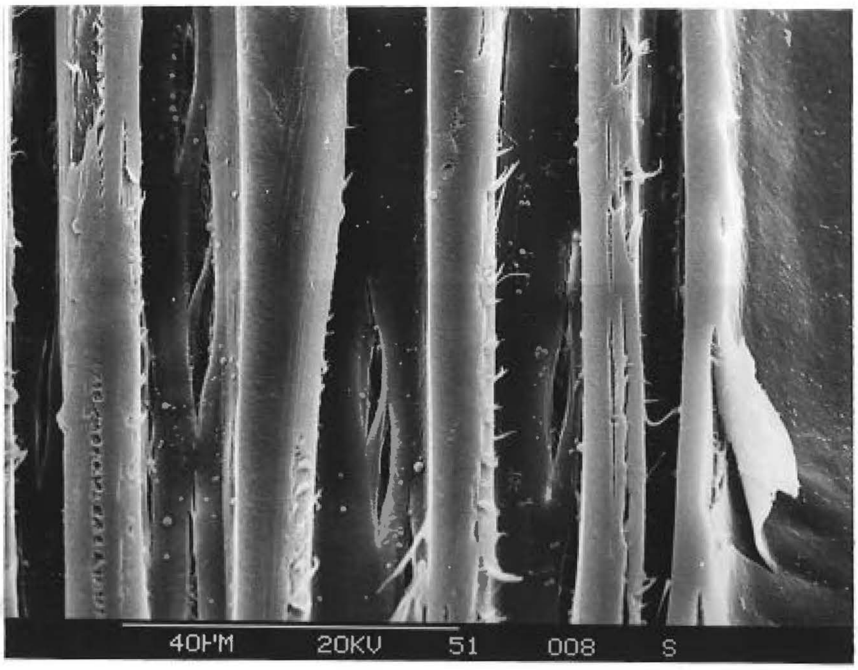


Figure 7.41 SEM; Radial section of N.fusca after hot soaking treatment showing longitudinal splits in the cell walls.

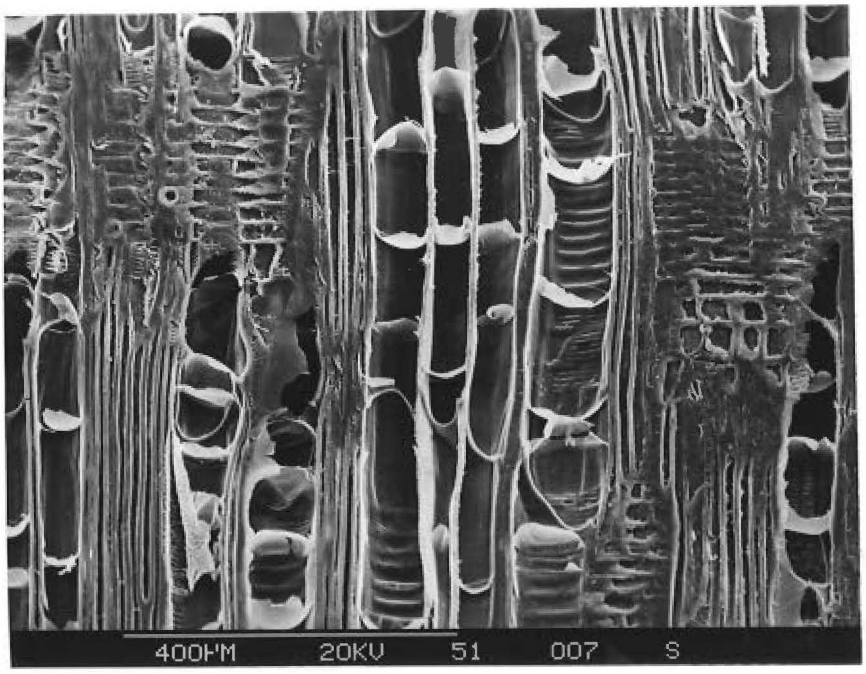


Figure 7.42 SEM; Radial section of N.fusca after hot soaking treatment with a number of vessels containing undamaged tyloses.

An unexpected macroscopic feature observed after hot soaking was the increase in board thickness from 25 to 26 mm on average, an indication of some swelling during the soaking process. This swelling, occurring when the moisture content of the wood is above the fibre saturation point and at elevated temperatures, probably arose from the expansion of trapped air (Schmidt, 1967) occluded in the void space, as the wood heated up

At high temperatures, an increase in internal air pressure, due to low permeability combined with the reduction in cell wall strength and shrinkage due to decrease in fibre saturation point (Weichert, 1963), are believed to be main factors responsible for splits observed in fibre walls. Haslett and Kininmonth (1975) had similar experiences testing the effects of steaming of Nothofagus fusca heartwood at 40% moisture content and 110% moisture content, whereby pretreatment at the higher saturation level led to a substantial degrade of the timber; steaming at 40% moisture content had a less severe effect.

A combination of hot water pretreatment and compression-rolling —induced microstructural alterations consisting in the first place of small cracks following the ray parenchyma (Figure 7.43).

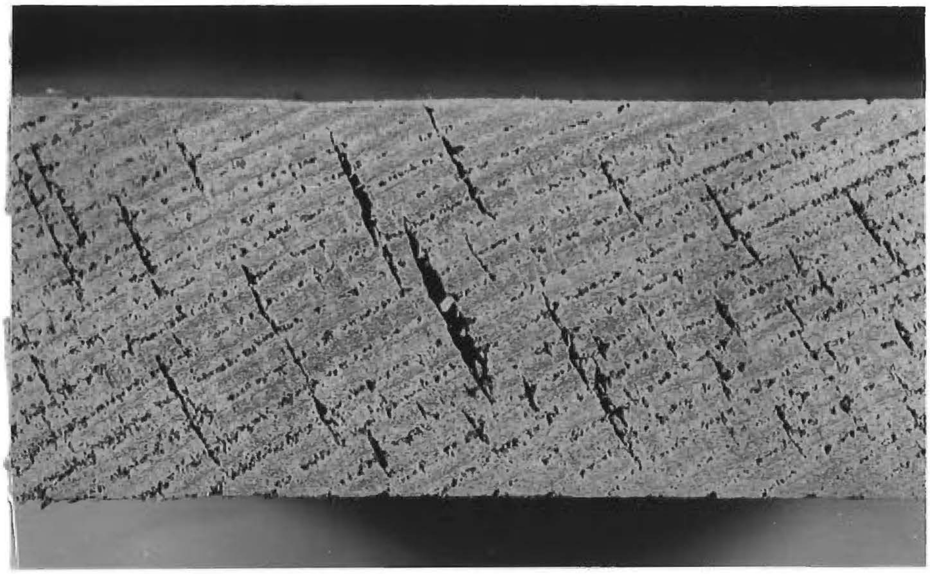


Figure 7.43 4 x magnification; Cross section of hot soaked rolled board of N.fusca with splits along the ray parenchyma (after rolling with the large roller, at 1000 mm/s and at the 10% compression level)

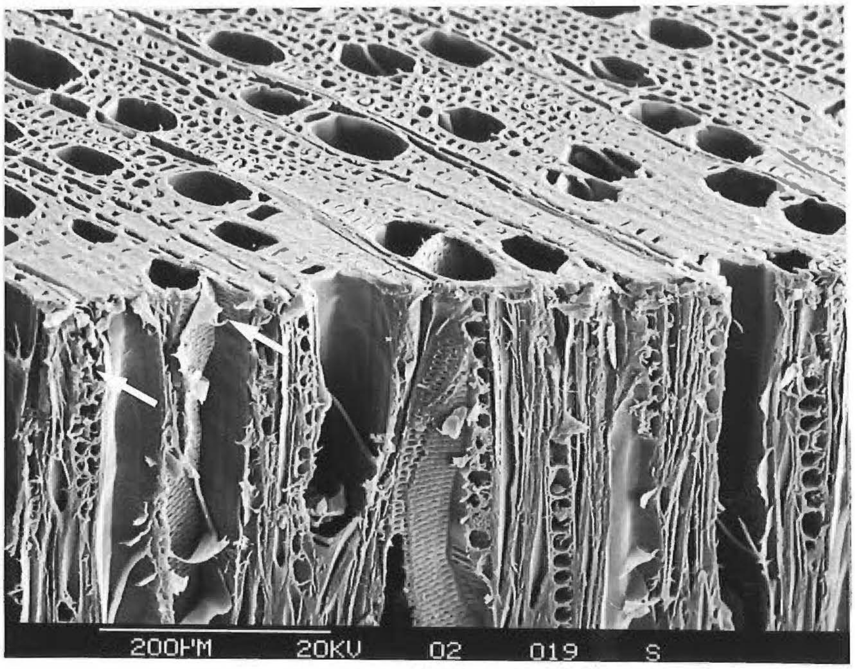


Figure 7.44 SEM; 3-dimensional section of N.fusca after hot soaking and compression rolling (conditions as in 7.43); arrows are marking the substantial damage on the tangential face in vessels and rays.

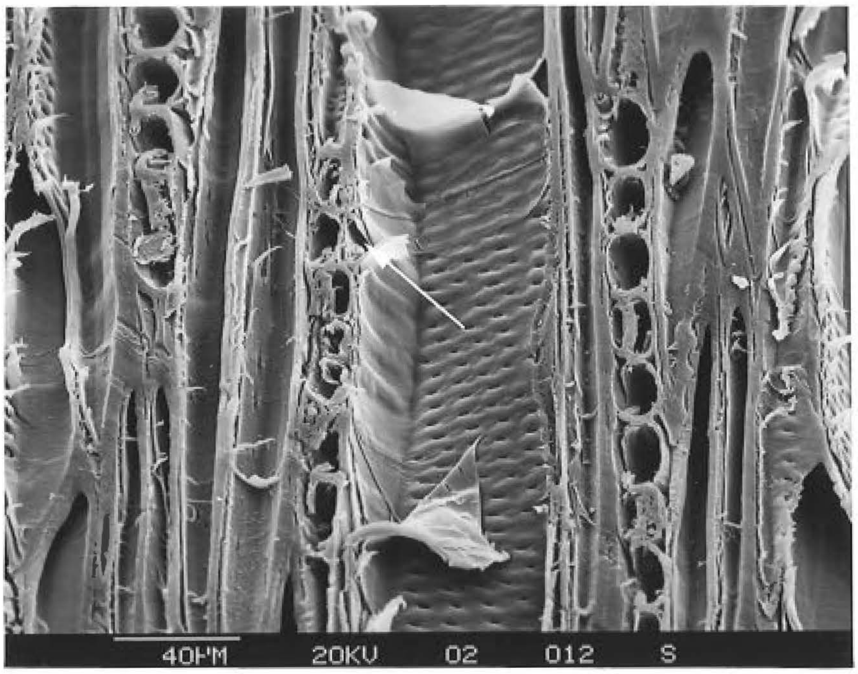


Figure 7.45 SEM; Tangential section of hot soaked, compression rolled sample of <u>N.fusca</u> with damage to the ray/vessel wall (arrow); (rolling conditions as in 7.43).

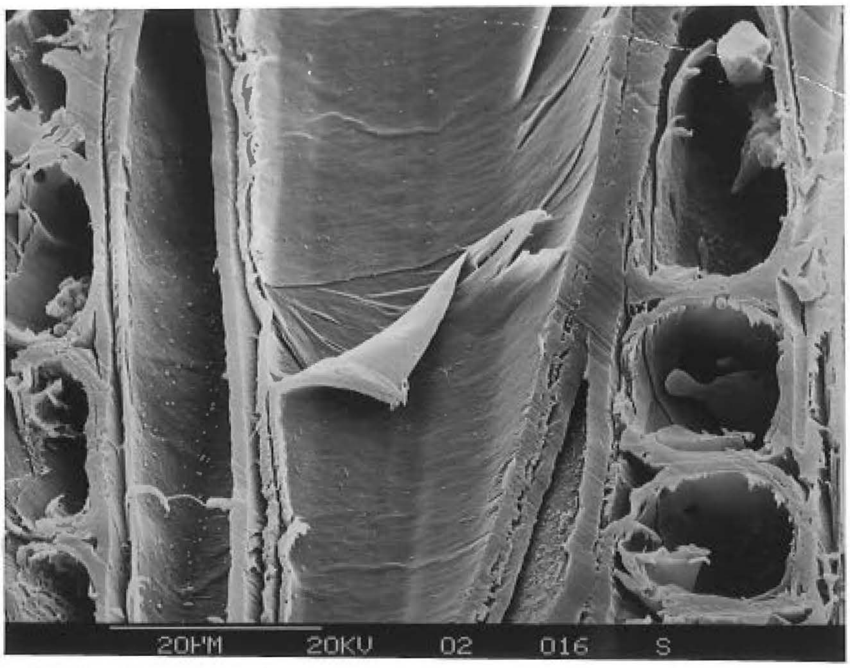


Figure 7.46 SEM; Tangential section of hot soaked, compression rolled board of <u>N.fusca</u> (rolling conditions as in 7.43), delamination within vessel wall.

In addition to the partial dilution and coagulation of the extractives substantial damage to the ray cell walls was detected. Representative illustrations of the microstructural alterations observed in the soaked and compression rolled boards are shown in Figures 7.43, 7.44, 7.45 and 7.46.

The effects of hot water soaking on the anatomy of Nothofagus fusca can be summarized as follows:

- Modification of extractives lining the cell wall cavities of the ray parenchyma, partially uncovering walls and pit membranes.
- Occasional longitudinal splitting of fibre pit membranes and fibre walls.
- Negligible effects to vessel walls, perforation plates and tyloses, which remain undamaged.

Hot water soaking and rolling at all three compression levels had the following consequences for the ultrastructure:

- Substantial macroscopic damage present in form of radial splits and occasional tangential checks along annual growth rings.
- In addition to the redistribution of the extractives, there is damage to the ray-to-vessel and ray-to-fibre walls (causing separation of cell types from each other which ultimately leads to the observed radial splits; Figure 7.48).

- Damage to vessels, perforation plates, tyloses and vessel wall components.

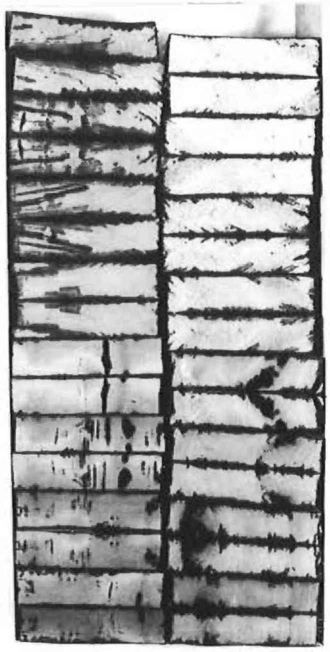
7.5 EFFECTS OF AN ADDITIONAL HOT SOAKING TREATMENT ON THE PERMEABILITY OF NOTHFAGUS FUSCA

Hot water soaking improved permeability of Nothofagus fusca heartwood to only a limited extent; indeed the increase in face penetration is negligible (Plate 7.3 and Table 1.611) compared to that observed after compression rolling. This finding is in agreement with Kininmonth (1971) who concluded his study on steaming of the same species by stating that "...steaming improves the rate of diffusion but does not affect permeability. It apparently improves access of moisture to areas of the cell wall including the pits without rendering the pit membranes permeable, i.e. it fails to reopen void spaces in the pit membranes..."

The importance of vessels as pathways for preservative penetration is once more demonstrated; since hot water soaking does not alter the structure of vessels nor does it damage the tyloses within their luminae, these cell elements remain unpenetrated.

Plate 7.3: Cross sections of _N.fusca_ after hot soaking and preservative treatment (chrome azurol spot test).

1) Controls
2) Boards of _N.fusca_ after hot soaking and rolling at 1000 mm/s and 7% compression
3) Boards of _N.fusca_ after hot soaking and rolling at 1000 mm/s and 10% compression
4) Boards of _N.fusca_ after hot soaking and rolling at 1000mm/s and 13% compression



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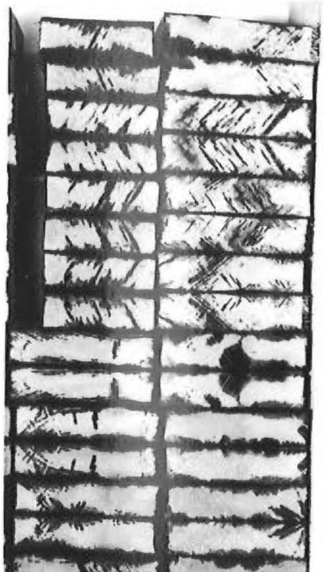

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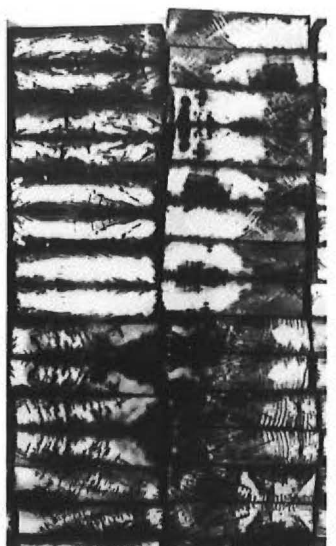

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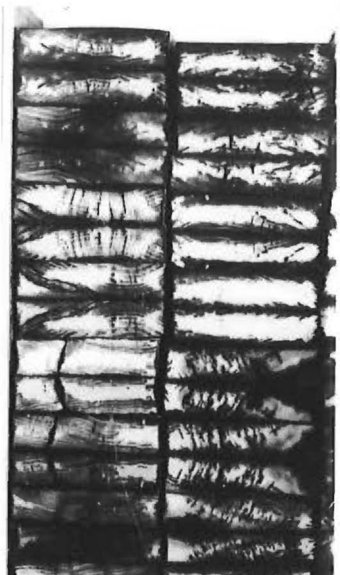


4

The combination of hot water soaking and compression rolling at all three levels increased the permeability substantially although to a lesser extent than for rolled unsoaked boards (Table 1.811 and chapter 6.4.4.2). This difference between unsoaked rolled and hot soaked rolled boards appears to have its origin in the different fluid redistribution during rolling. While in the former the accessible pathways for fluid displacement during rolling are enclosed by relatively stiff cell walls and comparatively weak tyloses membranes, rolling boards immediately after hot soaking means that the wood is less stiff. It is hence less resistant to the rolling-induced pressure waves and the strain is subsequently dissipated in relatively larger area, (see chapter 6). In addition, hot soaking weakens the ray parenchyma and its connections to the surrounding tissue, which under dynamic pressure conditions act as additional pressure relief pathways. The distribution of the pressures induced through hot rolling is indicated by the location of microstructural damage. Plate 7.3 (levels 1, 2 and 3) demonstrates the characteristic penetration pattern for hot water soaked and rolled boards for the three compression levels 7%, 10% and 13%. Preservative uptake and penetration are quantified in Tables 1.813 and 1.913. The common observation for all treatments is that preservative presence is not limited to the surface where dynamic compression is most severe, but follows either growth rings in the tangential direction or penetrates rays. Preservative is distributed very unevenly and depth of penetration is irregular (Figures 7.47 and 7.48).

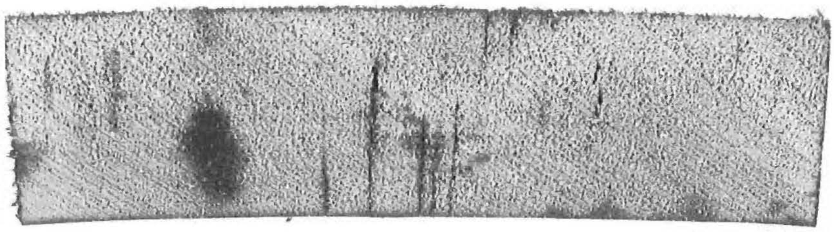


Figure 7.47 1 x magnification; Cross section of hot soaked control of N.fusca after preservative treatment (chrome azurol spot test).

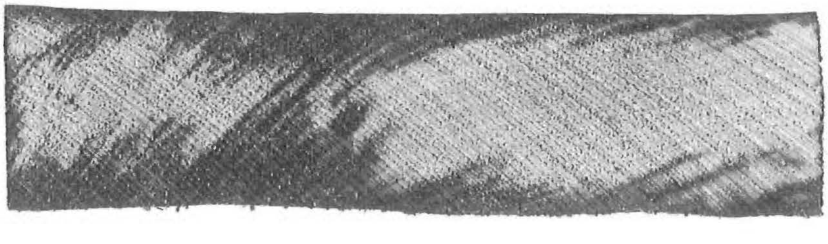


Figure 7.48 1 x magnification; Cross section of hot soaked and rolled board of N.fusca after preservative treatment (and rolling at 10% compression level with large rollers)

7.6 EFFECTS OF THE HOT SOAKING TREATMENT ON THE DIFFUSIVITY OF NOTHOFAGUS FUSCA

The hot water soaking pretreatment had a substantial effect on the drying rate of Nothofagus fusca heartwood, reducing the required drying time (in a very mild schedule) from highly saturated conditions to fibre saturation by 60 to 101% according to the grain orientation of the respective board (from 72 days to approximately 45 or 36 days respectively). The flatsawn boards dried faster and this can be attributed to the effective redistribution and partial extraction of phenolics from the ray parenchyma. This finding is similar to a previous report on the effect of steaming on drying of flatsawn Nothofagus fusca heartwood (Haslett and Kininmonth, 1975). A comparison of characteristic drying curves for hot water soaked control boards and non-pretreated compression rolled boards at high moisture contents is shown in Graph 5.4.

This suggests that the ray parenchyma tissue plays a major role in drying of a highly refractory timbers. In species with blocked ray cells all moisture present as free fluid in the cell luminae or as bound water in the cell wall moves to the surface by diffusion across cell walls (Stamm, 1963). A moisture gradient is slowly built up across the thickness of the board, since the outermost parts tend to dry out faster than the centre. Drying becomes increasingly more difficult and the drying rate declines gradually. If on the other hand the ray tissue is accessible and diffusion along the rays possible, "free" water vapor diffusion will be enhanced. Diffusion through the ray parenchyma is limited by the pit membranes, which offer less resistance to moisture movement than thick cell walls. Hence the moisture gradient between surface and centre of the board can be expected to be less pronounced while water vapor diffusion occurs at constant rate, until most of the free water is removed from the board.

The compression rolling of the hot water soaked boards did not lead to a further increase in drying rate. Hence pathways created to partially improve the permeability of hot water soaked boards did not contribute to drying. It appears that for transverse and axial drying a very important factor lies in continuity of pathways and available void space: although rolling created a series of fractures in the direct neighbourhood of the rays, as illustrated in chapters 7.4 and 7.5, drying is not enhanced.

7.7. EFFECTS OF ROLLING ON OTHER SPECIES

7.7.1. Influence of rolling on the anatomy of *Picea sitchensis*

The deformation of softwoods in compression perpendicular to the grain is not only a function of the cell wall strength characteristics, but is to a great extent influenced by the "stability of the form" (Frey-Wyssling and Stuessi, 1948) or the "stability of equilibrium". These authors describe the behaviour of softwoods under such loading conditions as a function of the geometry of the cells and of their arrangement as a whole. Therefore the compressibility of a softwood is influenced by a series of factors, such as variation in density between earlywood and latewood (Boutelje, 1962), the resistance of the rays to buckling, (Frey-Wyssling and Stuessli, 1948) and further by the geometry of the specimen (Kunesh, 1968). These reflections have to be considered in the following description of the rheological behaviour of *Picea sitchensis* during and after compression rolling.

Observations at the macroscopic level after the compression rolling of quartersawn boards at 20 % moisture content, at all three compression levels, revealed an unexpected phenomenon. The originally planed top and bottom surfaces had become corrugated, with the earlywood bands being consistently raised above the latewood bands, the phenomenon was not observed in flatsawn boards. A probable explanation lies in the irregular deformation during compression rolling of the quartersawn boards. A somewhat similar phenomenon commonly observed in flatsawn timber is described as "raised grain or surface corrugation" (Hoadley, 1980; Panshin and de Zeeuw, 1980; Kollmann and Cote, 1968; Koehler, 1929) except in such cases the latewood bands appeared raised. This observation contrasts with our own, since rolling induces a "washboard-effect" only in the quartersawn boards, where the softer earlywood appears raised above the harder latewood.

According to the American Lumber Standards (Panshin and de Zeeuw, 1980) "raised grain" is defined as "...roughened condition of the surface of dressed lumber in which the hard summerwood is raised above the softer springwood, but not torn from it...".Koehler attributes raised grain to the changes in moisture content after machining, where "...the compressed springwood has the tendency to swell more than the summerwood with changes in moisture content and upon recovery from compression, will push the summerwood bands above the surface ...". Hoadley (1980) states that "...the acutely angled layers (of latewood!) are driven into the weak supporting layers of earlywood as they are cut and pass under the knife. Then they spring back and rise above the machined surface..." The impression is given that "springback" is due exclusively to latewood recovery, since he continues his explanation stating that "...in extreme cases, the cell structure of the supporting earlywood is so badly damaged by compression that upon springback, the layers of latewood actually separate..." This observation is not surprising since experiments to determine the MOE in the tangential direction between isolated earlywood and latewood layers for Pinus sylvestris (Boutelje,1962) showed substantial differences (300.0 N/mm^2 for earlywood and 1465.0 N/mm^2 for latewood). Unfortunately no attention is given in that paper to the elastic recovery of late-and earlywood. The only reference found in the literature, which mentions differences in tangential and radial elastic recovery from high strains (total recovery after 10 % tangential compression was 62 % from the original thickness i.e. 3.8% permanent compression while total recovery after 10 % radial compression was only 45 % i.e. 5.5% permanent compression), does not present an explanation for these results (Fukuhara and Yasuda, 1973). It appears that raised grain is an interactive effect between unequal recovery and variation in the degree of swelling of the denser and softer zones in wood.

Surface corrugation caused by compression rolling is purely related to a variation in elastic recovery since the defect is present immediately afterwards (Figures 7.49 and 7.50).

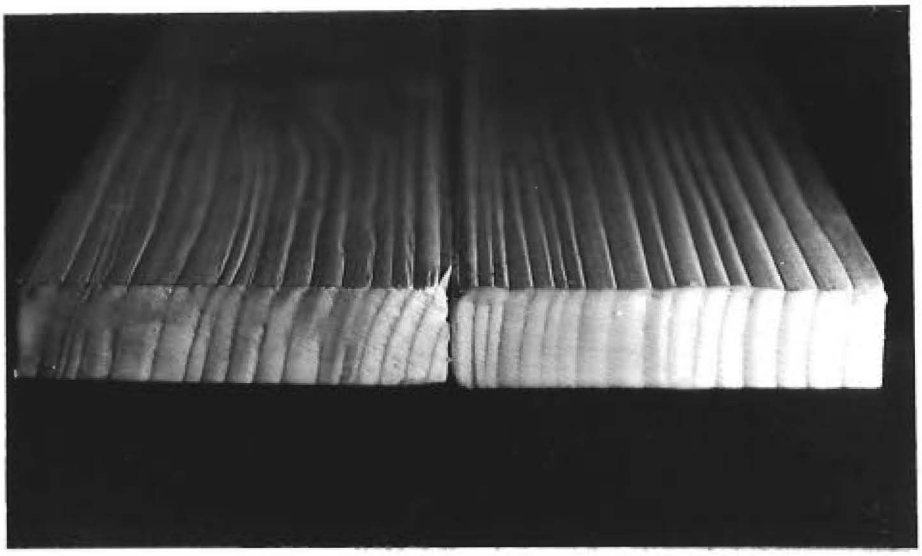


Figure 7.49; 0.5 x magnification; Cross section and top surface of rolled board of Picea sitchensis immediately after rolling (medium roller size: 121 mm diameter, 1500 mm/s feed speed and 10 % compression). Higher recovery of the earlywood compared to latewood leads to corrugation of the surface

Figure 7.50 0.5 x magnification; Cross section and top surface of a quartersawn board of Picea sitchensis immediately after rolling and of of a control (on the left); both boards were machine were machine planed before rolling and corrugation was only noticeable after compression rolling

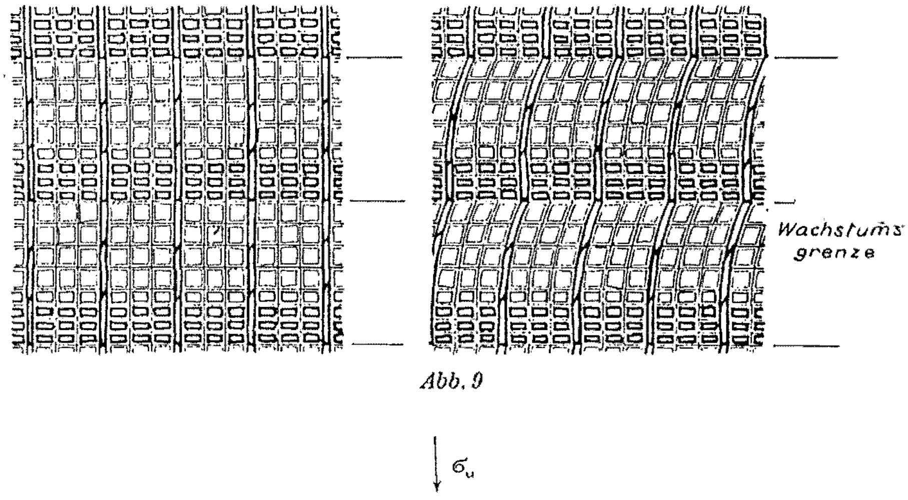


Figure 7.51 Model of softwood under compression perpendicular to the grain in the radial direction (According to Frey-Wyssling and Stuessli, 1948)

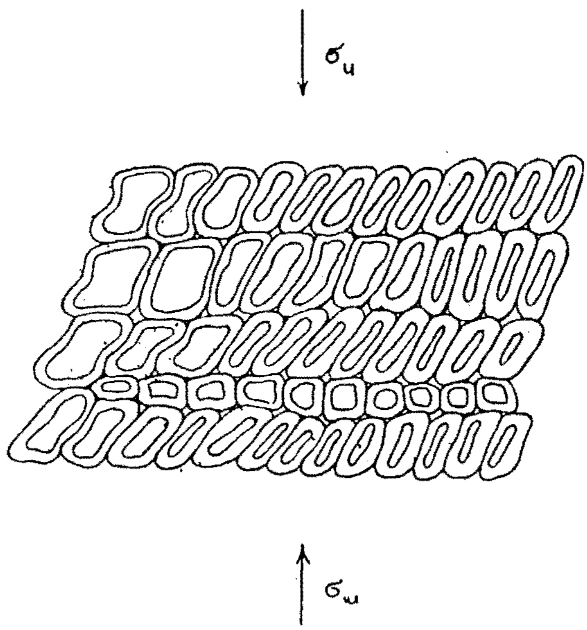


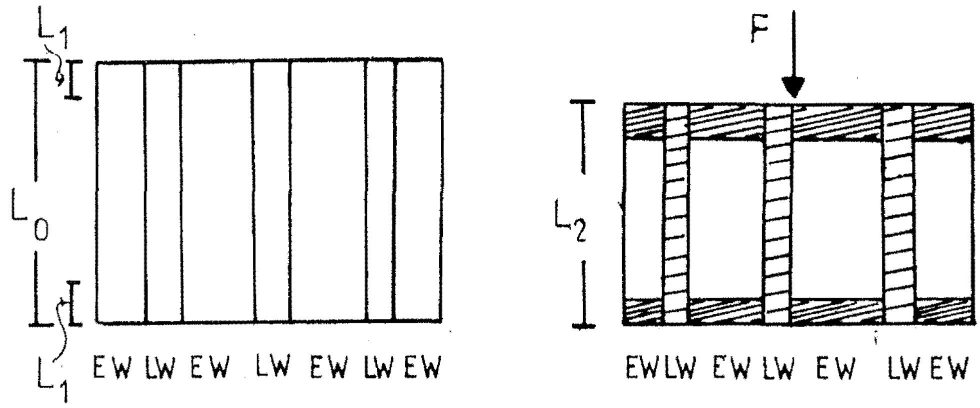
Figure 7.52 Model of softwood under compression perpendicular to the grain in the tangential direction (According to Frey-Wyssling and Stuessli, 1948)

While corrugations were only observed in quartersawn boards, buckling of stiffer regions (either latewood bands or rays) was noticed in both sawing patterns. In flatsawn, and less noticeably in the quartersawn samples, rays buckled in the zone of earlywood adjacent to latewood boundary and the deflection was similar to that described in Frey-Wyssling's model (Figure 7.51). During compression in the radial direction the rays function as principal load carriers through the earlywood. They can be regarded as a series of free standing slender columns embedded in a weak earlywood matrix. The large difference in lateral restraint offered by earlywood and latewood is responsible for the low stability of equilibrium of these columns, and their deflection in the earlywood approximates to that described by Euler's second case for determining the critical load of free standing columns (Popov, 1976).

During compression in the tangential direction (rolling of perfectly quartersawn boards) the difference in stiffness between earlywood and latewood leads to an uneven load-distribution, the latter being primarily borne by the stronger latewood. In addition a different strain distribution in the individual latewood and earlywood bands seems to occur. In the earlywood strain is dissipated near the top and bottom surfaces of the board, while in the latewood the strain is distributed more evenly across the thickness of the board (Figure 7.53). Thus when rolling quartersawn boards the deformation of the earlywood is confined to the surface layers whereas with the latewood the strain is more uniformly distributed through the surface and the central zones. The latewood bands can be compared with a series of columns, whose stability of equilibrium is influenced by the lateral restraint of the surrounding tissue, represented by the rays and the less stiff earlywood bands. Loss of equilibrium and deflection of the latewood will hence be influenced by the strength characteristics of the latewood fibres and by the stiffening resistance offered by the rays (in part a function of ray volume) and surrouding earlywood tissue. The earlywood in the surface zones shows greater recovery from even higher levels of strain compared to the adjacent latewood. This can be explained by a high elastic compressibility of the wide lumened fibre tracheids (compared in chapter 6 with closed cell elastic foams), in comparison to the stiffer latewood fibre tracheids with smaller luminae.

EW = Earlywood; LW = Latewood; = area under strain

F = Force ε = strain



($\varepsilon_{LW} = \varepsilon_{EW} = ((L_0 - L_2)/L_0) \times 100\%$; the total strain in the latewood and earlywood is constant

($\varepsilon_{LW} = ((L_0 - L_2)/L_0) \times 100\%$; the total strain in the latewood is dissipated over L_0

($\varepsilon_{EW} = ((L_0 - L_2)/2L_1) \times 100\%$; the total strain in the earlywood is dissipated over $2L_1$

Figure 7.53 Strain distribution across the thickness of a quartersawn board during compression rolling and variation in recovery between earlywood and latewood (see Figure 7.56 and 7.70)

The response of flatsawn timber to compression rolling is different. The strain distribution during dynamic compression of a perfectly flatsawn board of a species with substantial differences in the MOE of earlywood and latewood is illustrated in Figure 7.53A. It is assumed that the earlywood and latewood bands are planeparallel across and along the board, which of course very seldom occurs in practice. The distribution of strain in a less accurately machined flatsawn board, as shown in Figure 7.53C, can expected to be even more irregular. The method of edge-marking of boards (chapter 4) suggests such unhomogeneous deformation. This is not at all surprising as the weaker earlywood tissue is subjected to the same compressive stresses as the latewood and consequently one expects collapse of the cells in the earlywood bands near the board surfaces. Any analysis of the deformation in a broad sense - ignoring major local strain - can indicate only the general depth of deformation from either surface. Obviously the grid marking method to reveal strain is best suited to homogeneously structured timbers, for example diffuse porous hardwoods.

= area displaying most strain

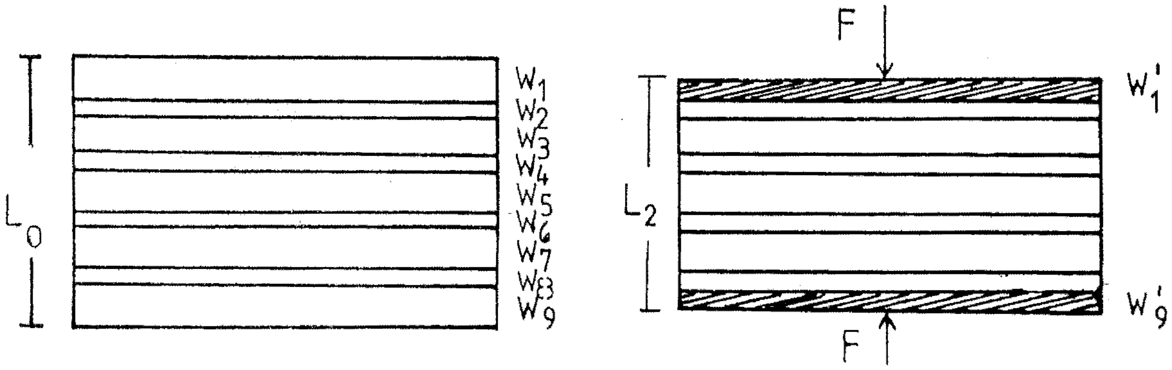


Figure 7.53A Schematic representation of the strain distribution across the thickness of a flatsawn board of Picea sitchensis during compression rolling

Case A: earlywood bands present on both top and bottom surfaces

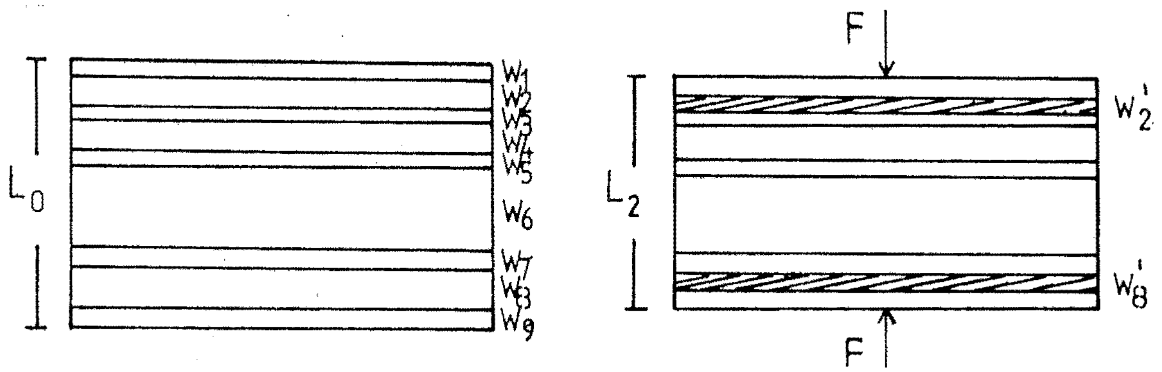


Figure 7.53B Case B: Latewood bands present on both top and bottom surfaces

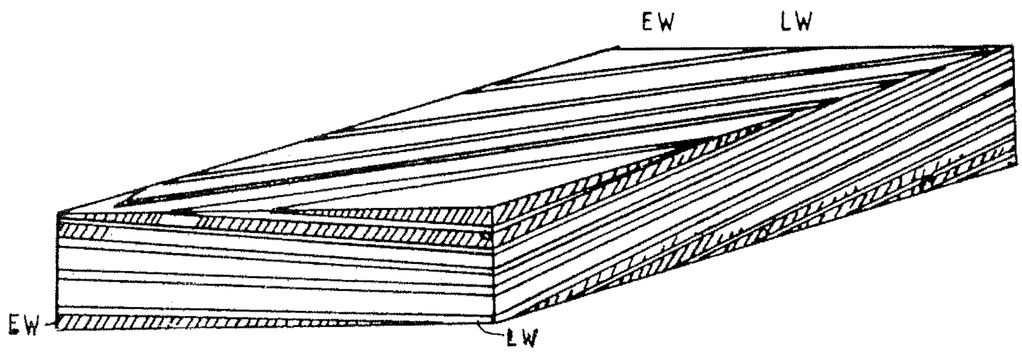


Figure 7.57C Case C: Poor alignment and irregular deformation in flatsawn board with non pefectly planeparallel earlywood/ latewood bands and expected irregupattern of deformation

A) Guide model in Figure 7.53A

W_1, W_3, W_5, W_7 and W_9 = Earlywood

W_2, W_4, W_6 and W_8 = Latewood

$$L_0 = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 + W_9$$

$$L_2 = W'_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 + W'_9$$

and so

$$L_0 - L_2 = (W_1 + W_9) - (W'_1 + W'_9) \text{ ,}$$

hence

$$\frac{L_0 - L_2}{L_0} \times 100\% = \frac{(W_1 + W_9) - (W'_1 + W'_9)}{L_0} \times 100\%$$

i.e. the total strain ε is dissipated in the earlywood at top and bottom surfaces (W_1 and W_9)

The localized strain in regions W_1 and W_9 is however

$$\frac{(W_1 + W_9) - (W'_1 + W'_9)}{(W_1 + W_9)} \times 100\%$$

B) Guide model in Figure 7.53B

W_1, W_3, W_5, W_7 and W_9 = Latewood

W_2, W_4, W_6 and W_8 = Earlywood

$$L_0 = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 + W_9$$

$$L_2 = W_1 + W'_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W'_8 + W_9 \quad ,$$

and so

$$L_0 - L_2 \; . \qquad (W_2 + W_8) - (W'_2 + W'_8) \quad ,$$

hence

$$\frac{L_0 - L_2}{L_0} \times 100\% = \frac{(W_2 + W_8) - (W'_2 + W'_8)}{L_0} \times 100\%$$

i.e. the total strain ε is dissipated in the two earlywood zones imediately below the top and bottom surface (W_2 and W_8)

The localized strain in regions W_2 and W_8 is however

$$\frac{(W_2 + W_8) - (W'_2 + W'_8)}{W_2 + W_8} \times 100\%$$

This interpretation of the deformation was affirmed by microscopic analysis of rolled boards where, in addition, buckling of the rays was noticeable in the earlywood of both quartersawn and flatsawn boards. Permanent deformation of earlywood tracheids in the quartersawn boards (rolled with the medium size roller, at the 9% compression level and at 1500 mm/s, applicable to Figures 7.54 - 7.55) was only observed in the top and bottom surfaces of the board (Figures 7.56), whereas in the center the earlywood tissue remains unaltered (Figure7.54). However in the quartersawn boards isolated damage occurs in the latewood fibre-tracheids across the whole thickness of the board (Figures 7.57 and 7.59), although some latewood fibre tracheids remain unaltered (Figure 7.58).

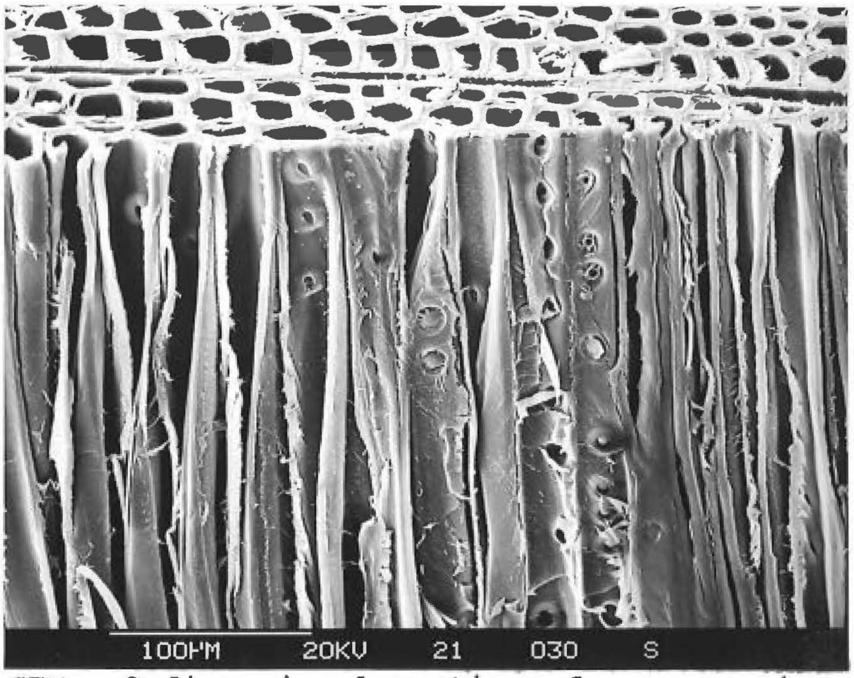


Figure 7.54 SEM; 3-dimensional section of compression rolled (medium roller diameter, 9% level of compression and 1500 mm/s feed speed), quartersawn board of <u>Picea sitchensis</u> with undeformed earlywood tracheids from the center of the board

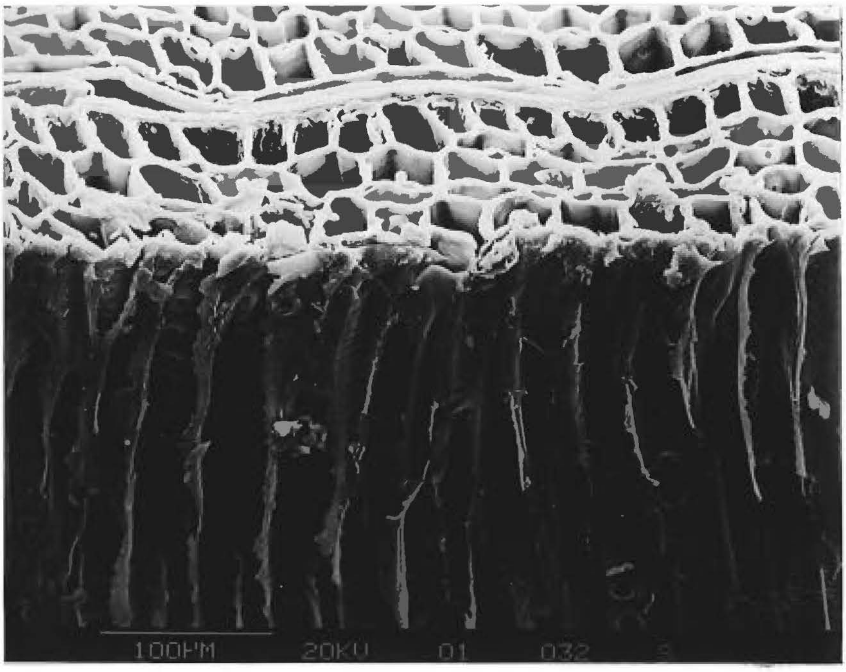


Figure 7.55 SEM; 3-dimensional section of compression rolled (conditions as for 7.54), quarter-sawn board of Picea sitchensis with deformed earlywood fibre-tracheids prepared from the surface of the board

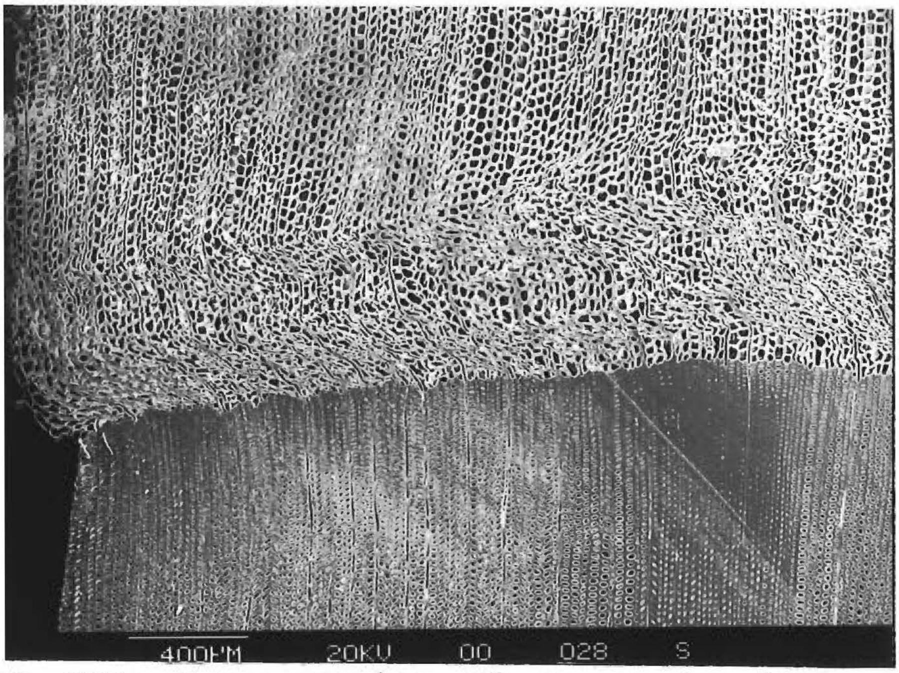


Figure 7.56 SEM; Cross section of a sample from a compression rolled, quartersawn board of Picea sitchensis (conditions as for 7.54) The left edge was prepared from the top surface of the board and it is noticeable that the earlywood appears raised above the level of the latewood

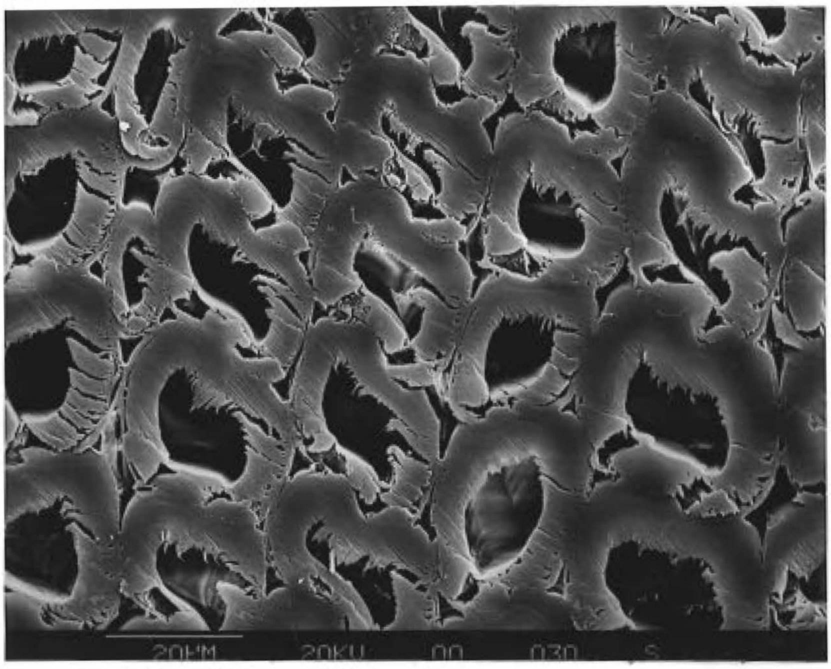


Figure 7.57 SEM; Cross section of a sample prepared from the center of a quartersawn rolled rolled board of Picea sitchensis latewood (conditions as for 7.54);the fibre tracheid walls appear deformed and damaged

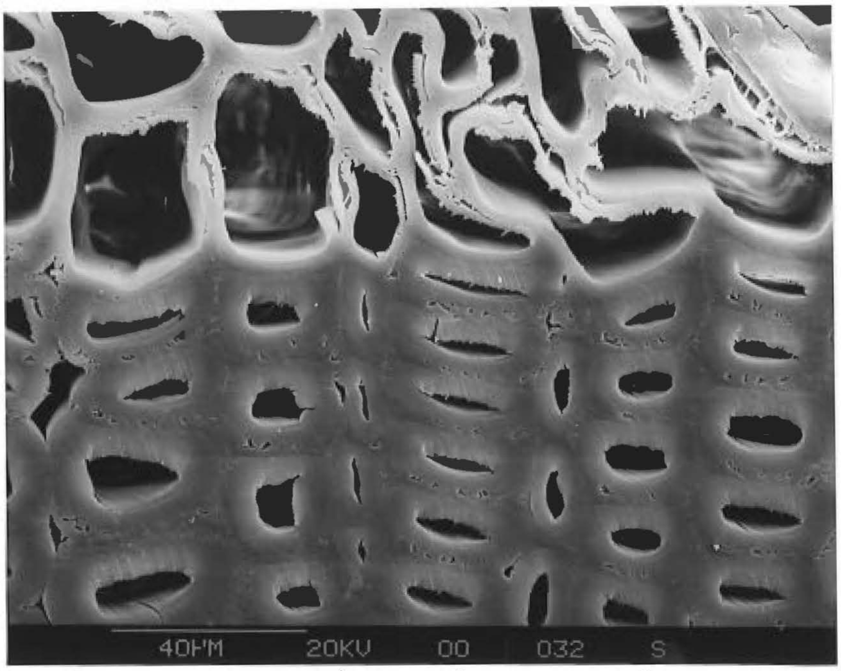


Figure 7.58 SEM; Cross section of a sample prepared from the surface of a quartersawn rolled board of Picea sitchensis (conditions as for 7.54) showing intact latewood fibre tracheids adjacent to deformed earlywood tracheids

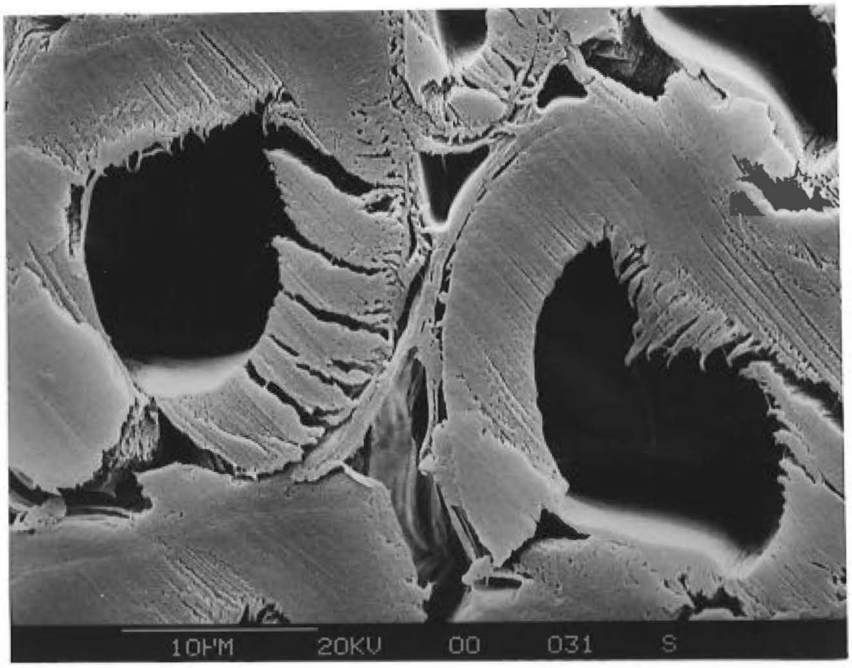


Figure 7.59 SEM; Cross section of a sample prepared from the center of a quartersawn rolled board of Picea sitchensis (conditions as for 7.54), showing damage to the latewood fibre tracheid wall and partly delamination of the middle lamellae.

7.7.2. Effects of rolling on the permeability of *Picea sitchensis*

Compression rolling increased the permeability of *Picea sitchensis* heartwood to a similar extent to that reported by other workers for *Picea glauca* (Cooper, 1973; Cech and Huffman, 1970; Cech, Pfaff and Huffman, 1974). The uptake of CCA preservative solution as a percentage increase in weight varied from 58.4% to 116.5% for the rolled boards against 47.2 to 84.4% for the unrolled controls. Experiments were not fully replicated, hence the results cannot be interpreted statistically, however the difference in penetration pattern between rolled and non-rolled boards is notable (Figure 7.60).

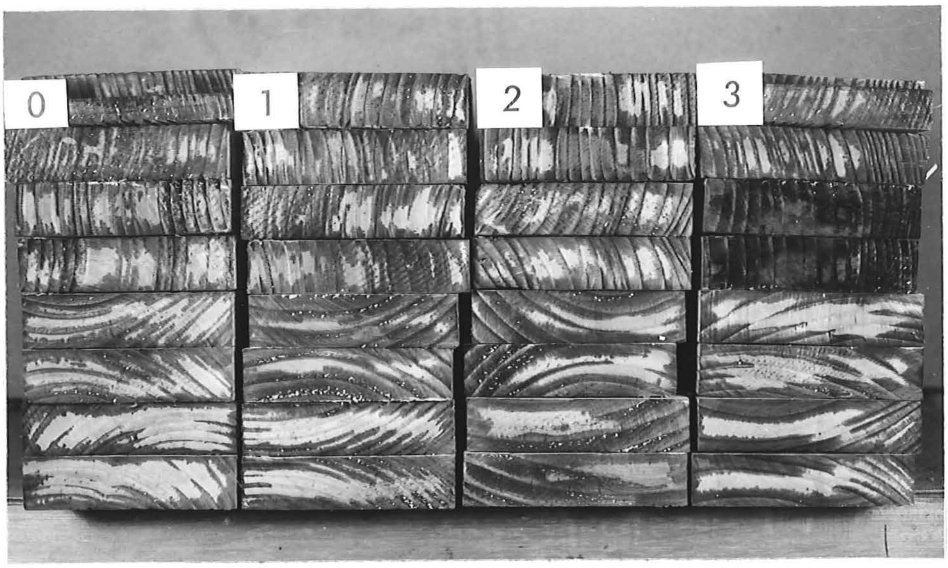


Figure 7.60 Cross sections of preservative treated boards of *Picea sitchensis* heartwood with similar irregular penetration pattern at levels 1 (6% compression), 2 (9% compression and 3 (12% compression) in comparison to unrolled controls (0).

The increase in permeability can be attributed to the structural changes in the earlywood tracheids, the occasional separation between earlywood and latewood (Figure 7.64) and to some extent to damage in the latewood pits.It is noticible that the fracture of pit membranes is restricted to individual tracheids within the latewood, where aspirated and unaspirated pits show signs of pressure damage (Figures 7.61 and 7.62):

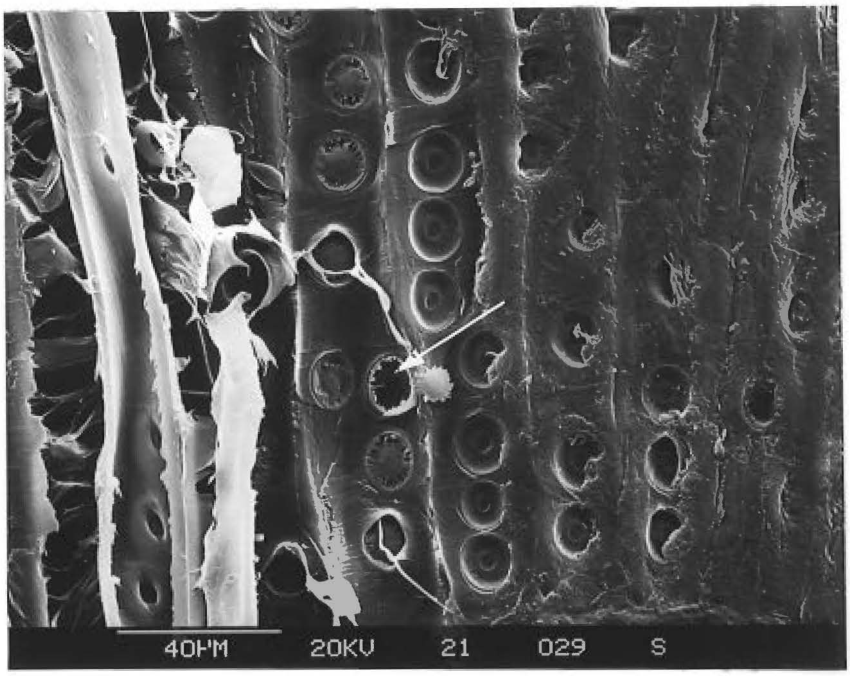


Figure 7.61 SEM; Radial section of Picea sitchensis latewood after compression rolling (condition as for 7.54) with ruptured unaspirated pit membrane (arrow)

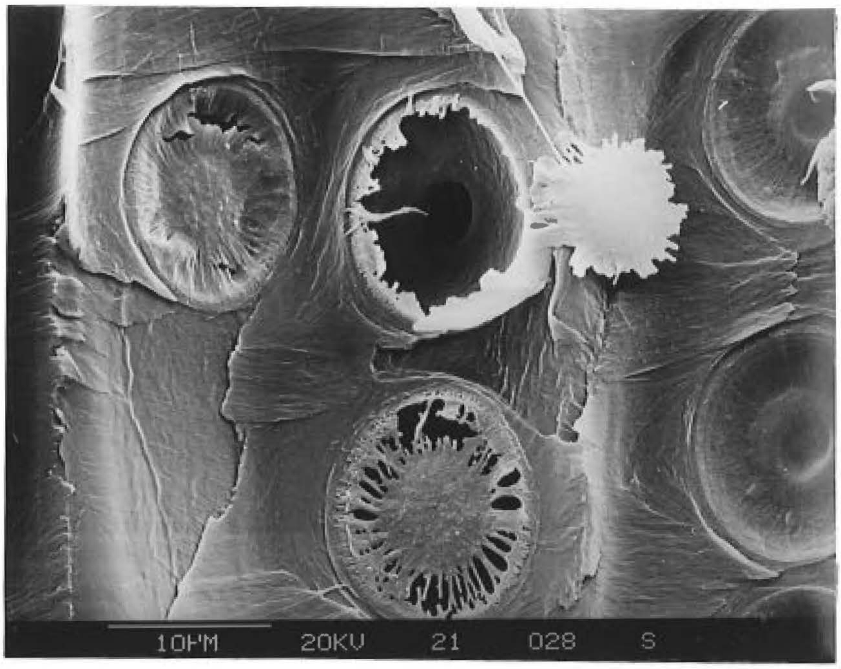


Figure 7.62 SEM; Radial section of Picea sitchensis latewood after compression rolling (conditions as for 7.54) illustrating the damage to unaspirated pit membranes in various stages

The damage to the pits cannot be attributed solely to the rolling process, since pressure treatment and preparation techniques can cause additional damage. Rupture of pit membranes occurs only in a small number of latewood fibre tracheids and was not observed in the earlywood, unless fracture had occurred in the wall.

The susceptibility of the earlywood to collapse during vacuum/pressure preservative treatments is a further factor to be considered in the analysis of damage. After rolling the earlywood appeared raised but the earlywood collapsed during the pressure treatment, (Figures 7.63 and 7.64), causing the latewood to appear as raised grain.

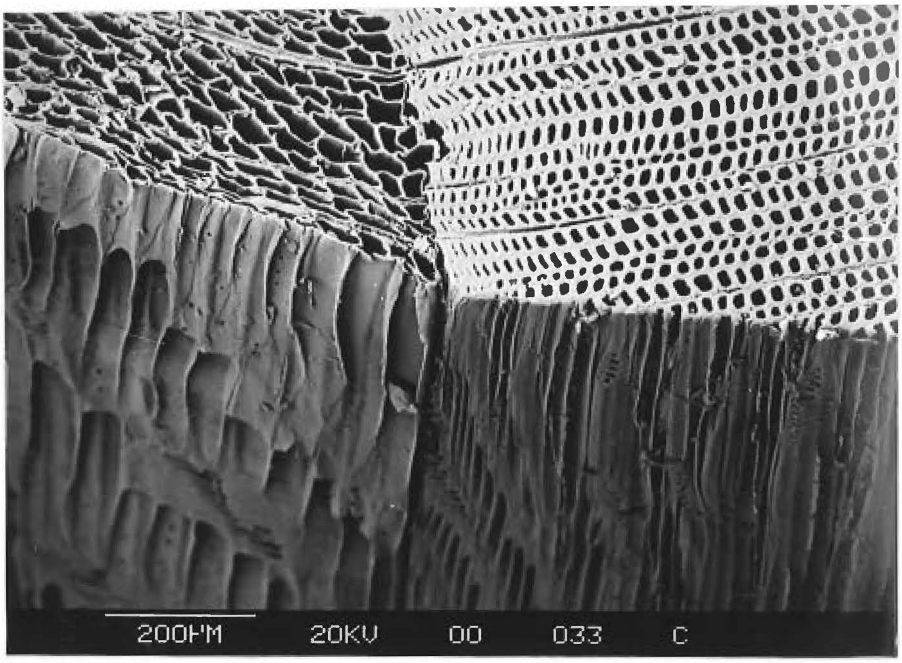


Figure 7.63 SEM; 3-dimensional section from compression rolled and preservative treated board of Picea sitchensis with collapsed earlywood on the left side (conditions as for 7.54)

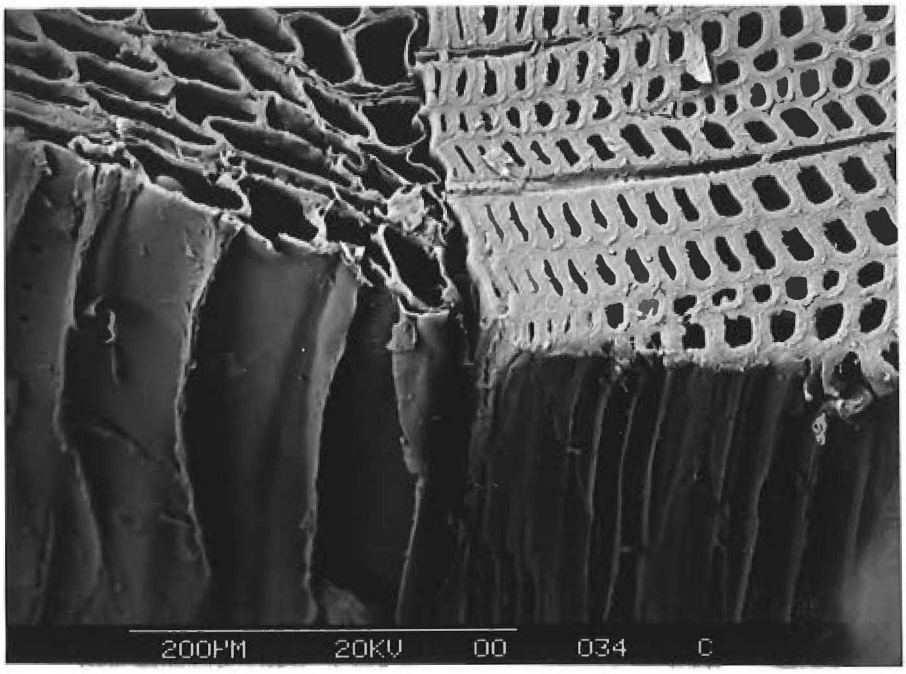


Figure 7.64 SEM; 3-dimensional section from same board as 7.63 showing earlywood separated from latewood at the growth ring boundary.

Collapse of the earlywood bands during pressure treatment was noticeable in both rolled and unrolled samples and the effect was greatest for the quartersawn boards, indicating that the low resistance to pressure in the earlywood of spruce is inherent rather than attributable solely to the compression treatment. Structural changes especially affecting the earlywood and the ray tissue are common for pressure treated Sitka spruce, as reported by Riechert (1974), (Figure 7.65). He attributes the extreme collapse observed in very high pressure treatments with Anilin-blue dye (33 kPa initial vacuum, 30 min; 8000 kPa pressure for 60 min.) to the difference in density between earlywood and latewood. While the density of the earlywood was 260 kg/m^3 the latewood density reached vlaues up to 840 kg/m^3, in comparison Kollmann and Cote (1968), report earlywood/latewood density values for the same species of 300 kg/m^3 and 900 kg/m^3 respectively. According to Riechert, a further reason for the high susceptibility to collapse within the earlywood of <u>Picea sitchensis</u> lies in its low permeability. ".. Eine Ursache fuer die Druckempfindlichkeit kann die schlechte Wegsamkeit sein, die auch den Splint durch niedrige Aufnahmemengen kennzeichnet...". He observed an increase in preservative uptake with an increase in pressure although he attributes these results to the creation of cracks and splits rather than alterations at the microscopical level, "...Daraus kann gefolgt werden, dass die betraechtliche Mehraufnahme nicht auf ein druckbedingtes Oeffnen zusaetzlicher Eindringwege im mikroskopischen Bereich beruht, sondern auf das Aufreissen der aeusseren Abdichtung und dadurch entstandenen zusaetzlichen Eindringwege zerueckzufuehren ist..."

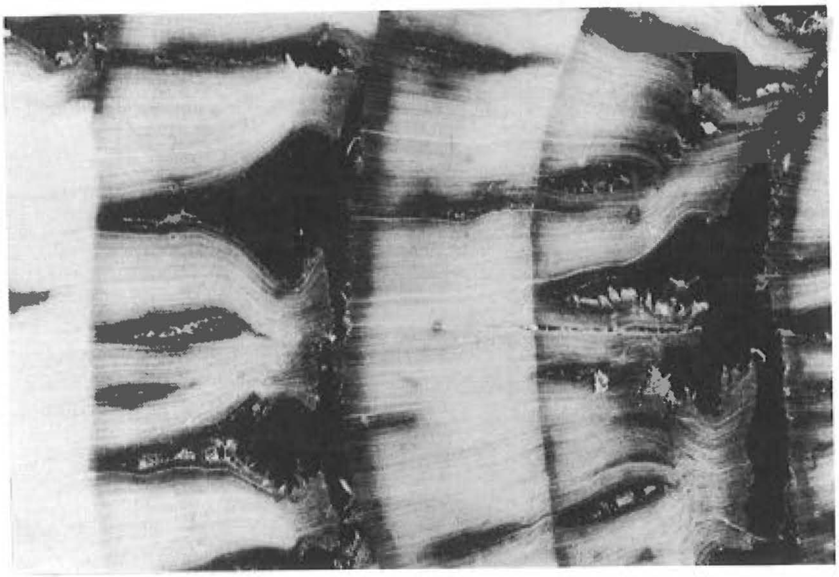


Figure 7.65 Damage in ray tissue of high pressure treated spruce. (According to Riechert, 1974)

Pressure: 8000 kPa, 60 min.
Vacuum: 33 kPa 30 min.
Preservative: Anilin dye

7.7.3 Influence of rolling on the anatomy of *Pseudotsuga menziesii*

Similar macroscopic effects to those described above for *Picea sitchensis* were observed in quartersawn boards of *Pseudotsuga menziesii*, subjected to a 10% dynamic compression at a moisture content of 20%. The feed speed during rolling was approximately 800 mm/s. The greater part of the earlywood in quartersawn compression rolled boards appeared raised above that of the latewood leading to corrugations of both top and bottom faces of the board. Microscopical examination showed that the damage pattern was very similar to that noticed in rolled Picea sitchensis.

- Earlywood fibre tracheids appeared deformed and occasionally the cell walls were fractured; rays in the earlywood located near either of the surfaces of the board were bent towards the surface following the general tendency of the earlywood to bulge out; occasionally some buckling within the ray parenchyma occurred (Figures 7.66, 7.67 and 7.68). Fracture and deformation of the different cell elements was restricted to the surfaces, whereas the cell structure in the centre of the board remained unaltered.
- Damage in the latewood was restricted to the middle lamellae between adjacent fibre tracheids, which showed substantial dilamination to such a degree that continuous splits appear perpendicular to the

external faces of the boards, indicating that the latewood is subjected not only to compressive but also to shear stresses. Shear failure not only affects the fibre tracheid walls (Figure 7.69) but in addition the ray parenchyma is often interrupted or simply translocated. This, to a great extent, is caused by fibre tracheids sliding past one another in the tangential direction (Figure 7.72).

- Fracture within the secondary walls of tracheids is not apparent in either earlywood or latewood. The structure of pits and pit membranes generally remained unaltered (Figure 7.73 and Figure 7.74) although in areas of substantial macrostructural damage pits were also damaged (Figure 7.68).

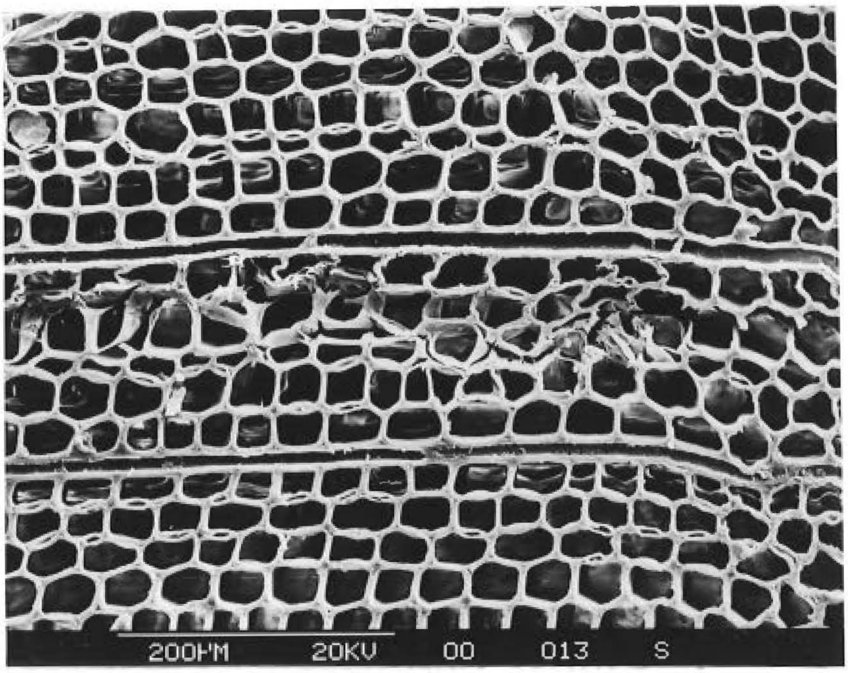


Figure 7.66 SEM; Cross section of sample prepared from the surface of a compression rolled board of Pseudotsuga menziesii (medium roller diameter, 1000 mm/s feed speed and at 10% compression level); showing deformed early-wood tracheids

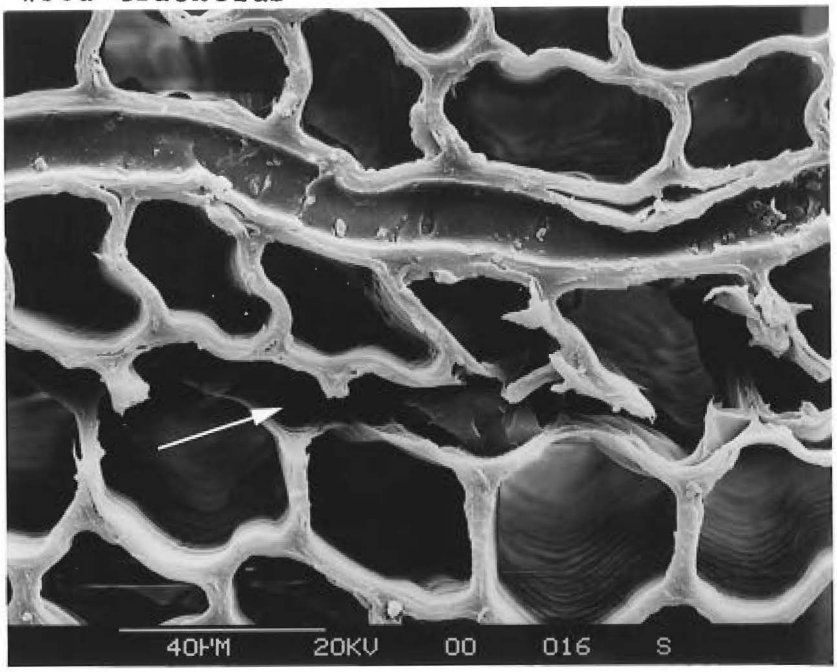


Figure 7.67 SEM; Cross section of sample prepared from the surface of the same board as 7.66. A continuous split (arrow) runs parallel to to the ray in otherwise little deformed earlywood

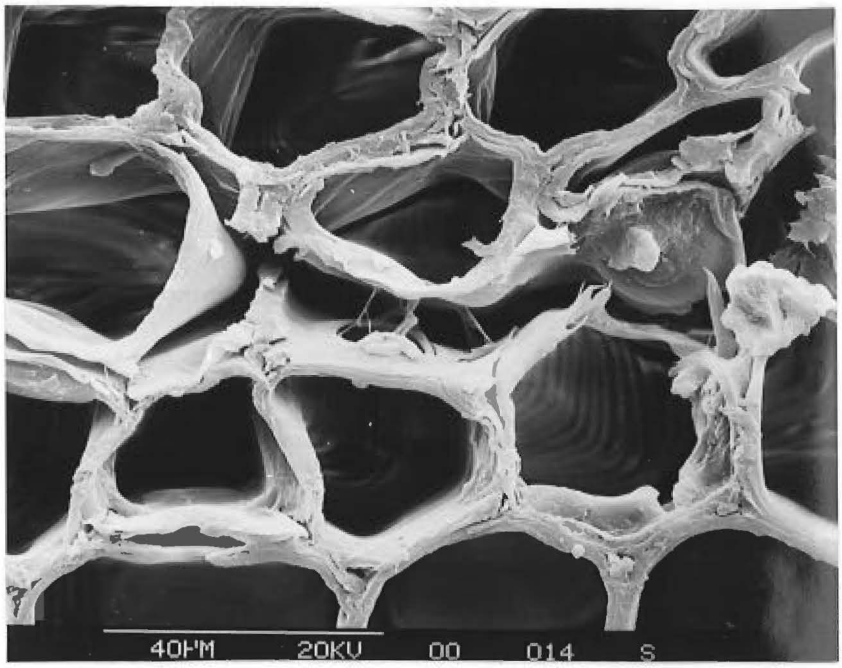


Figure 7.68 SEM; Cross section of sample prepared from the surface of the same board as 7.66, which illustrates the separation of fibre-tracheids within in the earlywood and the substantial damage to the cell wall

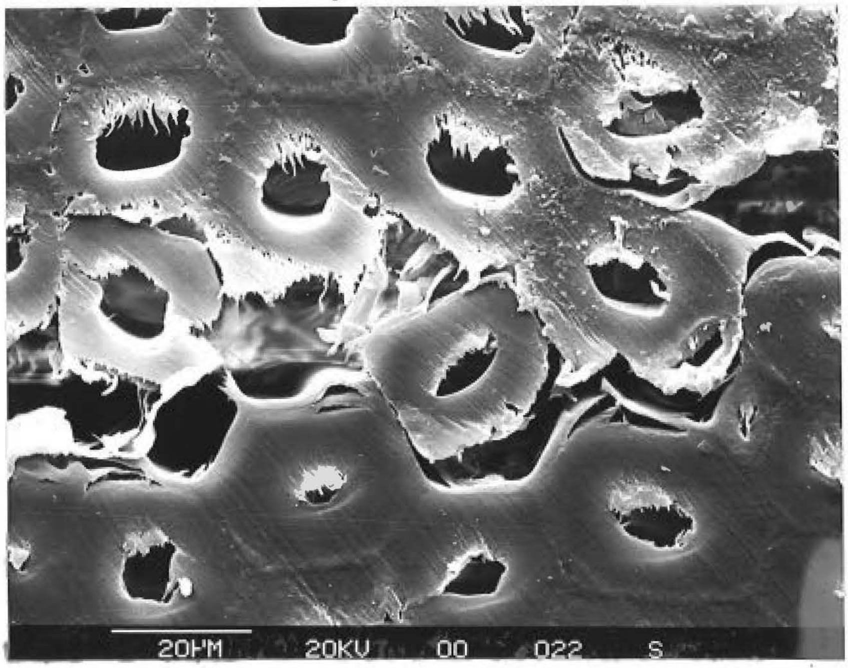


Figure 7.69 SEM; Cross section of sample prepared from the surface of the same board as 7.66, delamination occurs in the middle lamellae between latewood fibre tracheids creating intercellular voids.

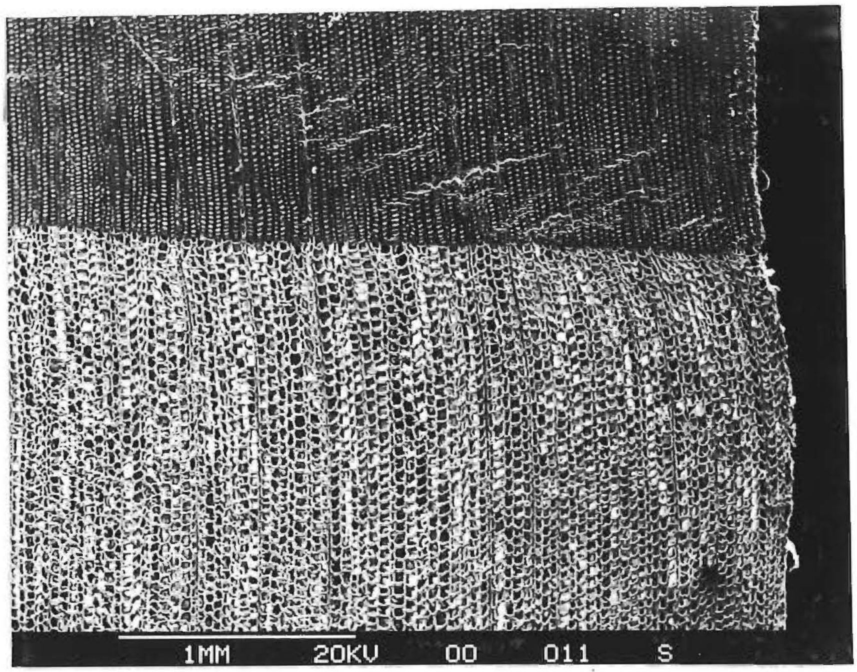


Figure 7.70 SEM; Cross section of sample from the same board as 7.66. The right edge is identical with the top surface of the board where the earlywood is similarly raised above the latewood as described earlier for Picea sitchensis (Figure 7.56)

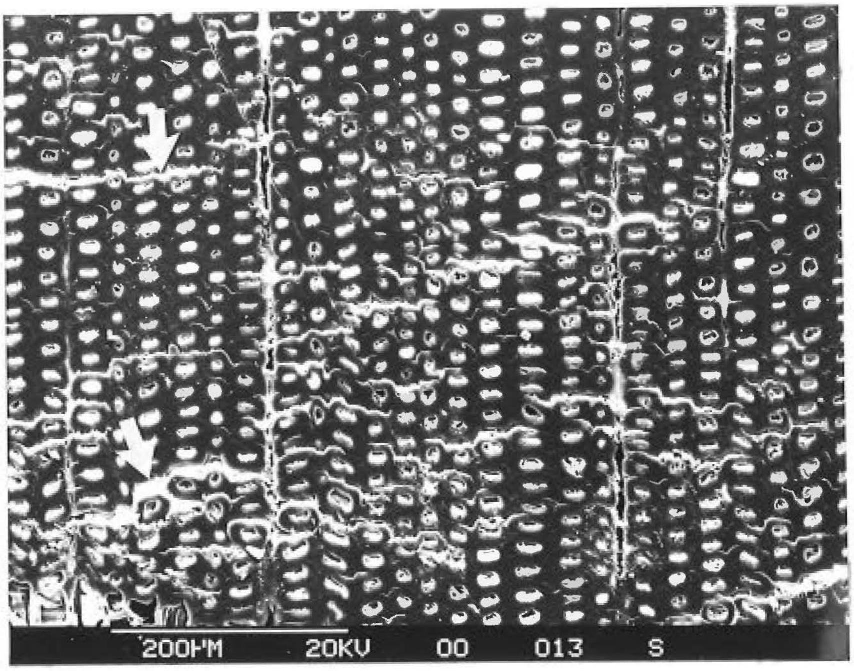


Figure 7.71 SEM; Cross section of sample from the same board as 7.66.Separation of fibre tracheids in the latewood leading to continuous tangential splits as marked by the arrows.

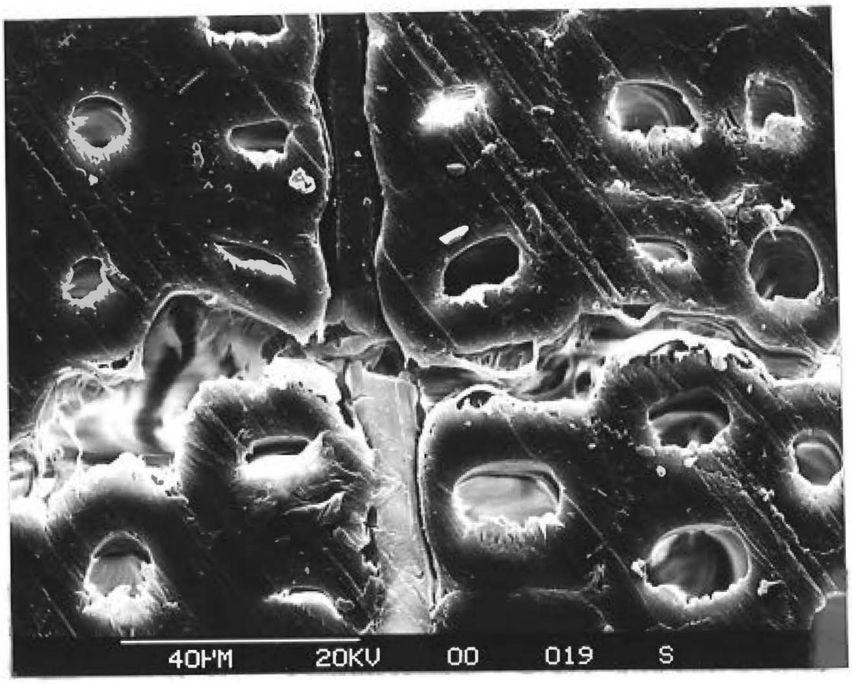


Figure 7.72 SEM; Cross section of sample from a board rolled under identical conditions as those applicable for 7.66.A continuous tangential split between latewood fibre tracheids causes complete interruption of the ray. It is also noticeable that the delamination occurs between middle lamellae and secondary wall.

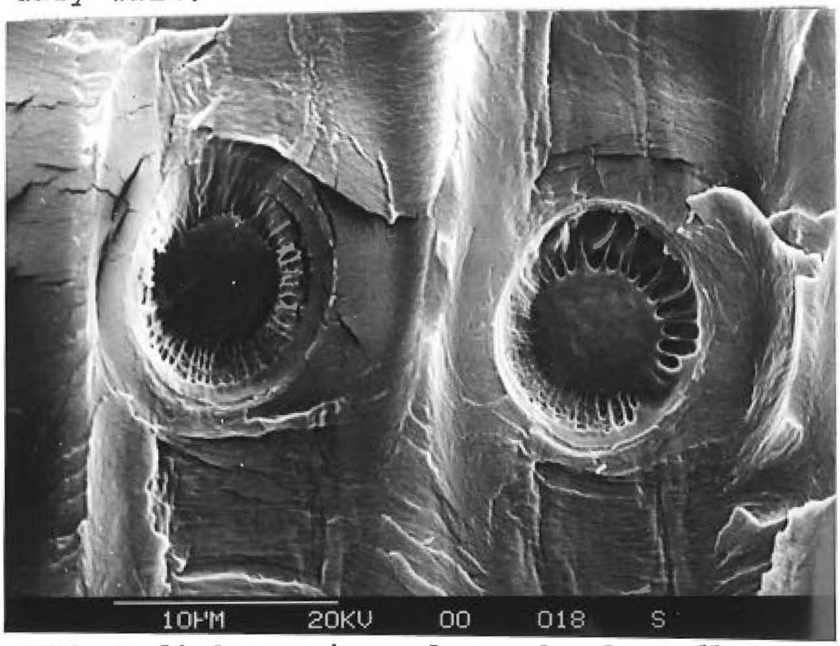


Figure 7.73 SEM; Radial section of sample from flatsawn compression rolled board of Pseudotsuga menziesii (conditions as for 7.66). Aspirated pit membranes in earlywood fibre-tracheid prepared from the deformed zone on the surface showing no signs of damage. This was representative for the whole area.

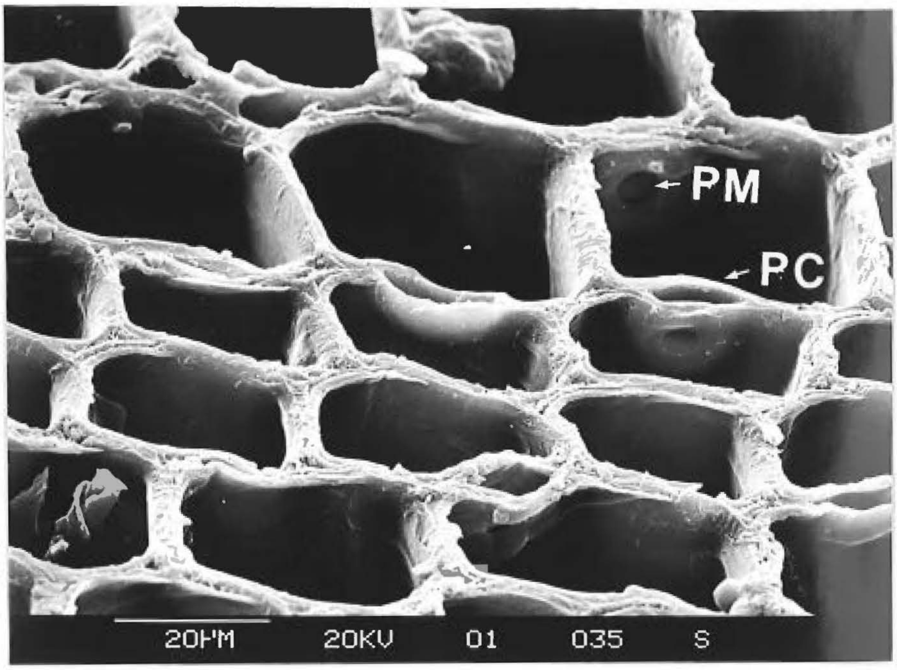
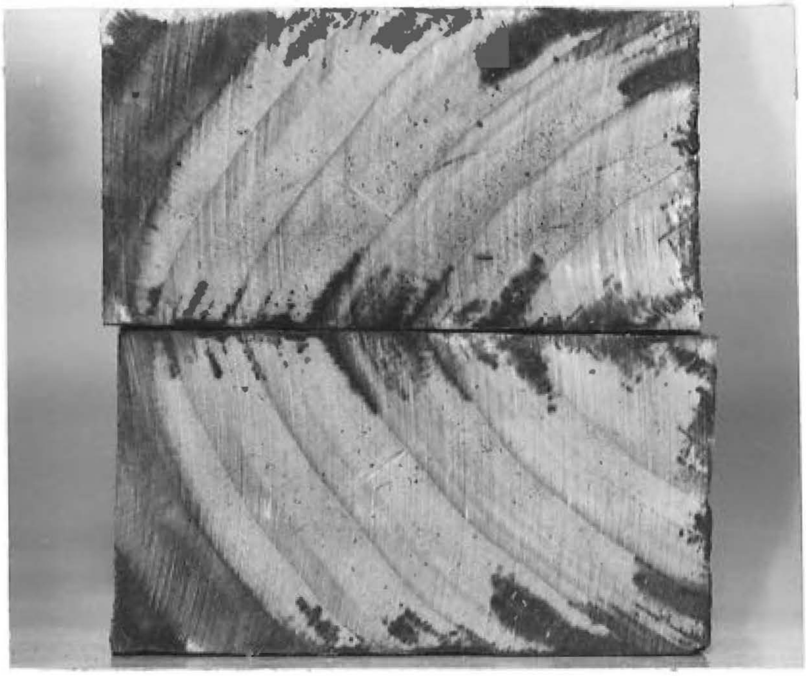


Figure 7.74 SEM; Cross section (inclination 45^{o}) of sample from compression rolled board of Pseudotsuga menziesii with intact pit membrane (PM) and pit chambers (PC) in deformed earlywood fibre tracheids (conditions as for 7.66)

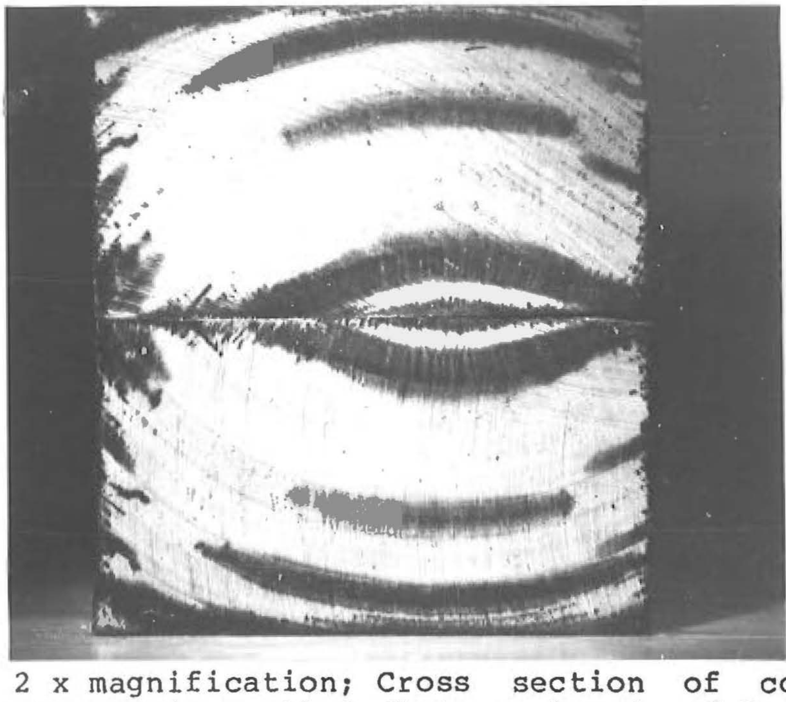
These observations confirm the earlier findings with Picea sitchensis leading to the conclusion that elastic compressibility of wood is not only a function of the elastic properties of the cell wall and the stability of equilibrium, but to some extent it is influenced by its permeability. As indicated in chapter 6, the elastic properties of wide lumen cells are dependent on the fluid contents of the lumen and on whether they can be readily translocated, when subjected to high strain.

7.7.4. Effects of rolling on the permeability of *Pseudotsuga menziesii*

These preliminary rolling experiments with *Pseudotsuga menziesii* did not confirm suggestions by other authors (Nicholas, 1973; Cooper 1973), that a substantial improvement in preservative uptake of flatsawn heartwood can be achieved with the process, although comparison between results is difficult, since their rolling conditions were not described. Preservative uptake of a small number of test specimens was slightly increased in compression rolled boards, although penetration was restricted to small bands in either latewood or earlywood zones, (Figures 7.75 and 7.76). Often penetration pathways coincided with cracks or splits caused during rolling. The main barriers for preservative access to the tracheids, aspirated pit membranes, in both earlywood and latewood did not show signs of damage.



Fiqure 7.75 2 x magnification; Cross section of compression rolled (large roller size, 1000 mm/s feed speed and 10% compression) quartersawn board of Pseudotsuga menziesii, after preservative treatment with CCA-salts, complete penetration of sapwood (arrow), whereas the heartwood only shows little penetration.



e 7.76 2 x magnification; Cross section of com-compression rolled flatsawn board of Pseudotsga menziesii (conditions as for 7.75); limited penetration in heartwood restricted to small bands mainly in the latewood.

CHAPTER 8 : INTERPRETATION AND DISCUSSION OF RESULTS

8.1. DRYING OF HARDWOODS

It has been postulated that compression rolling is a potential pretreatment for sawn timber of refractory species, in order to reduce the drying time and/or to ameliorate the drying characteristics (Goulet and Cech, 1967; Goulet, 1968; Cech and Goulet, 1968; Cech, 1971; Cech and Pfaff, 1975; Cech and Pfaff, 1977). The increase in drying rate was attributed to minute failures within the pits of some cell elements (vessel to vessel pits) and it was apparently demonstrated that the process was particularly effective for woods with low inherent permeability (Cech, 1971).

These conclusions were not confirmed in the course of experiments with *Nothofagus fusca* heartwood, a New Zealand native species of very low permeability and slow drying characteristics due to heavily encrusted pit membranes in vessels and in ray parenchyma (Kininmonth, 1970) and to the abundancy of tyloses in the vessels. Neither preliminary tests by Haslett and Kininmonth (1975) nor comprehensive experiments conducted by the author gave results which would endorse the application of the process to increase the drying rate of *Nothofagus fusca* heartwood.

The effects of compression rolling on the ultrastructure of red beech were to a great extent dependent on the level of saturation at the time of rolling. High levels of saturation (above 90 %) lead to extensive macroscopic failure within the earlywood. Damage was concentrated in the first place on radial vessel-to-vessel walls which in extreme cases lead to a complete delamination between individual growth rings. Occasionally splits also extended across growth rings mainly following the ray parenchyma. A subsequent increase in drying rate was related to the larger surface available for evaporation or internal migration. Compression rolling at lower saturation levels around 50% did not damage the wood to the same degree but neither did it influence the drying rate. Microscopic examination of rolled boards (at both saturation levels) partially confirmed observations reported by Cech (1971) and Grozdits and Chauret (1981) since pit membranes in vessels frequently appeared damaged, although this could not be attributed solely to the rolling process but also to drying and specimen preparation induced artefacts.

According to permeability studies by Kininmonth, (1970) during drying of red beech sapwood "...principal pathways of flow are along the rays in the radial direction and from vessel to ray to vessel in the tangential direction. The latter seems to be less direct..." His results illustrate the importance of radial pathways in drying as against the tangential pathways. For sapwood the ratio between drying in radial and tangential direction was 1.62 : 1 which was very similar to the ratio between radial and tangential integral diffusion coefficients, 1.64 : 1. These were determined from an experiment in which the samples were conditioned in a constant climate room (relative humidity: 83.7 % , 28 ^{o}C) and then transfered into a similar chamber of drier climatic conditions (relative humidity: 57.4 % and 28 ^{o}C). The integral diffusion coefficient D was determined from the resulting desorption according to Boltzmann's form of Fick's second law of diffusion:

$$\bar{D} = (\Pi \times a^2 \times E^2)/16 \times t,$$

where

a = thickness (mm)
E = fractional moisture loss (%/%)
t = time (s)

The ratio between radial/tangential drying was less pronounced in heartwoods where it was found to be 1.3 : 1, while the ratio between the respective diffusion coefficients was 1.39 : 1. The slower drying rate of heartwood as against sapwood with a ratio of 1 : 5.7 for radial drying and 1 : 4.8 for tangential drying is attributed to extractives present in the tissue occupying most of the ray parenchyma luminae and also covering the pit membranes, which leads to a reduction in vapor diffusion especially within the ray parenchyma. The importance of vapor diffusion through ray cells during drying of hardwoods was mentioned by Stamm (1967), who indicated (inspite of disregarding this diffusion component in his theoretical calculations) that "...this (vapor diffusion through ray cells) might be quite significant, especially in the case of hardwoods...". Ray to ray pits and ray to vessel pits are regarded as the main limiting factors for transverse movement of fluids, either moving under a pressure gradient or down a concentration gradient.

Compression rolling as shown in this work only affects these pathways to a small degree, occasionally damaging terminal ray to vessel pits and vessel walls, without affecting radial ray parenchyma walls of ray to ray pits. The ratio of tangential to radial drying rate of rolled boards at medium saturation level was similar to that for the controls, which demonstrated that the damaged vessel to vessel pit membranes do not increase tangential drying to any significant extent (Graph 7.1).

Hot water soaking by itself and applied to boards which were subsequently compression rolled in the hot condition, reemphasised the importance of radial pathways in drying. Hot soaking appears to partially or completely clear extractives from the surfaces of the pit membranes and so decrease resistance to diffusion. Hot soaking had a greater effect on radial than on tangential diffusion pathways. Thus, the drying rate of flatsawn, hot soaked boards was increased twofold in comparison to flatsawn unsoaked controls, whereas quartersawn, hot soaked boards only dried 1.6 times faster than comparable quartersawn unsoaked controls.

Compression rolling after the hot soaking pretreatment did not lead to a further increase in drying rate, and only induced severe damage to the ray to fibre walls. Ray to ray parenchyma pits remained intact indicating that compression rolling induced displacement of fluids was restricted to axial pathways within vessels. No radial flow occurs within the rays. "Weak spots" or areas of stress concentration which allow limited transverse displacement of sap are located in the middle lamellae between ray parenchyma and adjacent fibre walls.

Cech states that the driving force during compression rolling lies in "...a hydraulic effect..." of displaced sap (Cech, 1971; Cech, personal communication, 1981). The author agrees that the hydraulic flow of sap can occur and has observed this phenomenon in red beech. However, these experiments showed that a pure hydraulic effect as observed during rolling of highly saturated boards (either cold or hot) had severe consequences for the timber structure (Figures 7.12, 7.13). Structural changes at the microscopical level could only be obtained without substantial damage by a less drastic " pneumatic effect " ocurring at lower saturation levels, where sufficient compressible gas was present in the cells. Excessive pressure may then be released by minute failure or cracks as observed in tyloses and perforation plates blocking the vessels (Figure 7.08). It may well be that partial damage to vessel to vessel pits in more permeable species can account for a moderate increase in drying rate as observed by Cech and Goulet (1968) for Yellow birch. But according to subsequent experiments on the same species (Cech, 1971) the variation between results indicates that little control can be exerted during rolling over microstructural alterations, which ultimately would lead to this increase in drying rate. This impression is reinforced by publications from other workers, who tested the effects of the process on other hardwood species (Berni and Christensen, 1979; Haslett and Kininmonth, 1975; Grosditz and Chauret, 1981).

8.2. TREATABILITY OF HARDWOODS

Compression rolling was also recommended as a pretreatment to increase preservative uptake in sawn timber of species of low inherent permeability (Cech and Huffman, 1970; Cech and Huffman 1972; Cech, Pfaff and Huffman, 1974;Goulet,Cech and Huffman, 1968; Cooper, 1973; Nicholas, 1973), although only the effects on softwood permeability have been examined. Consequently findings from this study concerning the effects of rolling on the treatability of red beech with preservatives can not be compared directly with results presented by these workers, since preservative penetration in hardwoods follows different pathways to those in softwoods (Thompson and Koch, 1971).

In contrast to drying, the ray parenchyma of hardwoods during pressure impregnation with preservatives do not participate and remain to a great extent unpenetrated. The most important paths for preservatives are vessels and to a lesser degree axial parenchyma and fibres (Siau, 1971). Blockages within the vessels such as tyloses or occluded axial and transverse vessel to vessel pit membranes are both present extensively in red beech heartwood, and reduce permeability significantly, as demonstrated by Kininmonth (1970). Therefore any attempt to improve permeability must concentrate on modifications to the vessel system. It has been demonstrated in the course of this work that a considerable improvement in permeability of red beech can be achieved by compression rolling, regardless of the treatment factors. This was primarily attributed to the extensive damage to tyloses and partly to the damage of the terminal ray cell pits and walls. However the microscopic fracture pattern and deformation of vessels was more pronounced in the earlywood, indicating that compressive strain and compression induced internal pressures within the timber were somewhat unevenly distributed during rolling. This influences quartersawn and flatsawn boards to the same degree; improvement in preservative uptake might hence be slightly higher for quartersawn boards in one experiment, while in the next experiment higher improvements can be recorded in flatsawn boards. Preservative penetration was concentrated in the earlywood, whereas the latewood was only penetrated to a limited extent, although the boundary between penetrated and non penetrated areas was gradual and coincided with the gradual transition from earlywood to latewood. These results are not unexpected. Some workers (Kininmonth, 1971; Juacida, 1970) suggest that such rupture of tyloses and other thin membranes may occur during pressure impregnation. However these authors did not conduct experiments to confirm this.

Only limited information is available on the axial permeability of red beech heartwood, except that it is categorized as impermeable. No published research has investigated the effects at the ultrastructural level of a high pressure treatment. As little is known about the variation in axial permeability of red beech we are obliged to note instead a study by Gonzales and Siau (1978) on low permeable American beech and _Eucalyptus_ spp. They present strong evidence"...of the presence of parallel longitudinal zones within the wood, containing tissue systems having significantly different permeabilities...". In a study on penetration pathways of liquid gallium in _Fagus sylvatica_, Trenard and Gueneau

(1984) also emphasize that regardless of an increase in pressure from 100 kPa to 1600 kPa during impregnation, complete penetration of all vessels was not achieved. This further strengthens the case that permeability varies widely between different zones of a single wood sample.

As discussed in chapter 5, impermeable wood species can be compared with elastic foams having closed cells which under high strains suffer internal damage in form of cracks in walls of individual cell elements. The distribution of this fracture pattern within the foam is even throughout the body, assuming cell dimensions and wall dimensions do not vary much. This is not so in wood, and hence the model can only be applied in approximation, to explain the fracture pattern and overall damage ocurring in highly strained timber. Factors such as porosity, cell wall dimensions and, not least, permeability are far from homogeneous. On the other hand, from MICROSCOPICAL observation of the fracture pattern it can be concluded that pathways made accessible during compression rolling as a consequence of the pressure wave coincided with subsequent pathways for preservative penetration. MACROSCOPIC splits and cracks caused by excessive pressures do not contribute to an increase in preservative uptake, although they increase the total surface exposed to the pressure treatment.

The impression is given that as long as compression rolling induces a displacement of cell void contents (either liquid or gaseous) through those pathways with less pressure resistant blockages, an increase in permeability in these zones can be achieved. In addition variability in the degree of deformation between the various cell types causes an uneven distribution of pressure during the rolling process and hence only part of the tissue, namely more compressible vessels (with higher inherent permeability), can function as a pressure relief system.

8.3. EFFECTS ON SOFTWOODS

The interaction between the effectiveness (in terms of increase in permeability) of compression rolling and intracellular variation in compressibility is even less predictable for softwoods in comparison to diffuse porous hardwoods. In addition to permeability fluctuations within a specimen, earlywood and latewood density variations and hence substantial differences in strength properties add to the irregular deformation (see chapter 7.7.1, Figure 7.53C) and hence displacement of cell void contents is to a great degree unpredictable. A further aspect which differentiates compression rolling induced flow in softwood from that described for hardwoods is the much lower ratio between longitudinal and transverse permeability, due to the absence of vessels in the former (Siau, 1971; see permeability values in Table 2.1). Hence transverse displacement of cell void content is thought to occur more readily in softwoods.

Flow in softwoods is primarily controlled by the structure and location of pit membranes in the tracheid to tracheid pits. If these are aspirated and isolate the adjacent tracheids from each other, flow is interrupted and the wood is less permeable. Pit aspiration is characteristic of the earlywood of low permeable species, such as Spruce, Cedar and Douglas Fir but it is less common in latewood (Siau, 1971; Phillips, E.W. 1933; Liese und Bauch, 1967). Experiments and processes dedicated to controlled deterioration of pit membranes by micro-organisms, which can be present in water stored timber, lead to a significant increase in preservative uptake (Archer, 1984; Unligil, 1972; Greaves, 1970). Little proof is provided that similar regular damage to the pit membranes occurs as a result of compression rolling. Neither Grosditz and Chauret (1981) who observed stretching of pit membranes after compression rolling _Pinus strobus_, nor Nicholas (1973) who attributes the increase in permeability of Douglas fir heartwood to damaged pits on the tangential tracheid walls, provide sufficient evidence for their respective explanations. The only pictures of ruptured pit membranes found in the literature (Cech, 1971; Figure 2.2) are related to vessel pits in Yellow birch, and it is suspiciously reminiscent of damage inflicted during specimen preparation. Yet it was this observation which was cited as evidence for compression rolling improving drying and permeability.

The theory that pit membranes can be deformed or ruptured was not confirmed in a study by Kučera and Bariska (1982). They investigate the effects of axial loading on the wood structure of softwood (_Picea sitchensis_) and of a hardwood (_Populus tremula_). According to their extensive SEM analysis it appears unlikely that pits and pit membranes in either _Populus_ or _Picea_ can be damaged by compressive forces. In _Populus_ the observation was that "...the vessel-to-ray pitting does not seem to induce any weakening of the vessel wall, nor are there any torn pit apertures. On the contrary, the crack runs between the pits.."(Figure 8.1.), whereas in *Picea* "...the bordered pits remain undamaged even in the most deformed tracheids..."(Figure 8.2).

From our own observations on Douglas fir and Sitka spruce heartwood (Figures 7.61, 7.62 and 7.73) it can be said that while there is some pit membrane damage during rolling, this is limited to the more permeable parts of the latewood. Aspirated pit membranes in the earlywood showed little damage, while unaspirated pit membranes within the latewood were often damaged along the entire length of individual tracheids. This indicates that these tracheids act as pressure relief systems during the compression cycle.

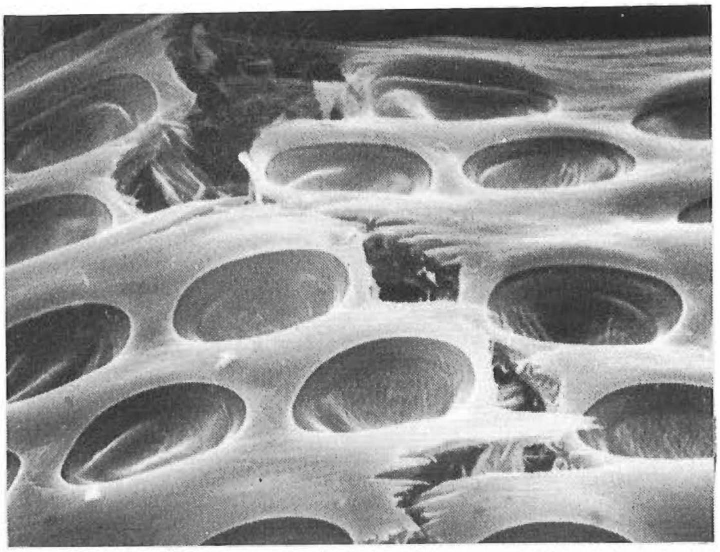


Figure 8.1 Damage to wall between pits as observed in Populus tremula according to Kučera and Bariska (1982)

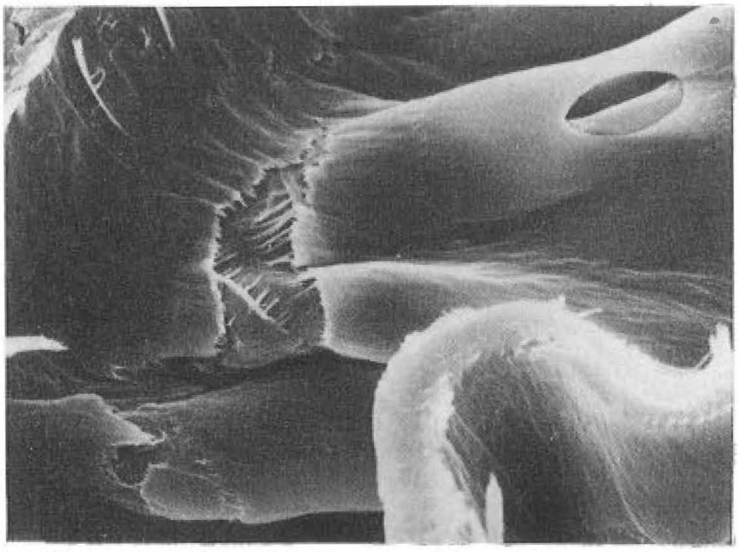


Figure 8.2 Damage in fibre tracheid; the pits remained undamaged in Picea sitchensis according to Kučera and Bariska (1982)

Most workers agree that the preservative penetration pattern in compression rolled species is concentrated to a great extent in the latewood, (Cooper, 1973; Cech and Huffman, 1972; Goulet and Cech, 1968), while areas of lower inherent permeability such as earlywood tracheids remain unpenetrated or insufficiently penetrated. These findings are also in agreement with observations made in the course of this work. In Douglas fir and Sitka spruce, with both compression rolled boards and controls, penetration pathways followed narrow bands within latewood, although a slight improvement in earlywood permeability was noticible in areas which had suffered substantial damage at the macroscopical level.

It can be concluded that displacement of the void contents in the earlywood tracheids is severly restricted in comparison to that in the latewood. This became evident in quartersawn boards. Immediately after compression rolling earlywood recovered to a greater degree than adjacent latewood. This supports the hypothesis suggested in chapter 6 that wood (or parts of it) with higher resistance to circulation of fluids through its void space is expected to carry greater short term loads without undue strain due to its greater damping capacity (Figure 6.8). Summarizing the effects of compression (= strain) across the thickness of a quartersawn board, it can be postulated that:

- The greater permeability of latewood in combination with a smaller void to cell wall ratio results in a low elastic compressibility. The high plastic deformation component can cause permanent collapse of the cell voids and also some shear failure between tracheids.

- The restricted permeability of earlywood and the greater void to cell wall ratio results in a greater elastic compressibility, which is primarily due to the closed fluid system in the lumens carrying high stresses (and experiencing increased internal pressures). Hence the reduction in cell void volume is recoverable after removal of the load.

8.4. DISTRIBUTION OF DEFORMATION DURING COMPRESSION ROLLING

The series of micrographs taken during the compression rolling of highly saturated boards of Nothofagus fusca (see chapter 4) was affected by the sap displaced from the timber. Figures 7.23 and 7.24 (chapter 7) show this effect, where the deformation of the grid circles near the rollers is not clearly distinguishable. Hence the interpretation of the grid pattern deformation during rolling was only considered qualitatively. It was evident that the deformation was not confined to the zone between the rollers but compression appeared to be initiated well before the board element first contacted the roller surface. This "strain propagation" was particularly noticeable during rolling experiments with the large roller size although a correlation between increase in roller diameter and length of strain extension was not established.

At the same time, it was indicated (chapter 7, Figure 7.53A) that the strain is not evenly distributed across the thickness of the board. A quantitative analysis of the grid pattern developed by Chu (1984) which determines longitudinal and transverse strains in one plane according to the ellyptical deformation of individual circles during different stages of the rolling cycle can therefore only produce approximate values; this is because Chu's analysis was designed for an incompressible and isotropic material. Compressive and shear forces (Chapter 7, Figures 7.69, 7.71 and 7.72, which originate during the compression cycle, interact with those induced through the pressure wave within the timber (Chapter 7, Figures 7.08, 7.09 and 7.11). The author considers that variation of strength properties (in particular modulus of elasticity) and variation in axial permeability within a board do not permit the exact determination and distribution of strains during rolling.

The observation regarding the differences in instantaneous recovery between earlywood and latewood wood in Pseudotsuga menziesii and Picea sitchensis (which has apparently not been noticed in previous rolling experiments and is not been described in the literature) is an aspect to be considered in future work.

8.5. CONCLUSIONS

Statistical analysis has concentrated on data regarding total uptake, average penetration and drying. Results analysed suggest that compression rolling represents a viable method to increase the quality of preservative treatment of low permeability hardwoods and softwoods. However it has to be emphasized that the overall improvement can be extremly irregular, especially in softwoods. Although it is possible to induce microstructural changes in timber with the process, it is extremly difficult to optimize and control the damage (keeping it limited to areas within the wood, which account for low permeability properties). Equally, one should not generalize from the experiences with one species to predict the effects of the process on another timber since little is known about the interaction between strength properties, wood structure and resistance to compression above the elastic limit perpendicular to the grain and permeability of timber.

Work to date including the findings of this study do not recommend the process for improving the drying characteristics of refractory hardwoods. Although studies on the effects of rolling for the drying of softwoods have not been undertaken so far, the microstructural alterations of the anatomy of rolled softwoods do not suggest that an improvement can be expected. This is based on the observation that compression rolling is unable to induce isolated damage in pit membranes, without at the same time affecting the surrounding tissue. Pits are the major pathways regulating drying and eventually the penetration of softwoods by preservatives. The adequacy of rolling as a potential pretreatment process to increase preservative uptake is hence equally questionable.

The process can on the other hand be recommended for four major fields of research:

1. Studies on the stress/strain interaction between machine and timber during rolling

   An important criteria for the design of the rolling device was the installation of dynamometer elements to allow measurement of loads and power consumption during rolling. A layout for adequate instrumentation was elaborated (Guenzerodt, 1982), which suggests the utilisation of microprocessors to guarantee accurate data recording and processing. The performance of this circuit is to a great extent dependent on the dynamometer elements, which had to be redesigned in the course of this work. Optimum instrumentation combined with photographic techniques capturing different stages of the compression cycle is believed to give important information about the rheological behaviour of wood under dynamic loading.

2. Studies on the permeability of diffuse porous, medium density hardwoods

It has been demonstrated that rolling is an appropriate method to improve the axial and tangential permeability of _Nothofagus fusca_, a medium density hardwood of low inherent permeability due to occlusions in the vessels. It would be useful if the study could be extended to other similarily structured refractory hardwoods and eventually the effects on ring porous timbers should be tested in detail. Research should concentrate on species of great commercial interest which often can not be preservative treated to the required standards (_Fagus sylvatica_, _Quercus spp._, _Populus spp._)

3. Studies on the possibility of impregnating timber using the vacuum occurring during the decompression phase

It was suggested initially, that the vacuum present in the timber during instantaneous and delayed recovery could be used to introduce solutions into the timber for different purposes (timber preservation, controlled biodegradation with bacteria solution). The present study did not investigate this possibility and it remains to be tested if the compression rolling-induced temporary pressure gradient will be great enough to produce sufficient transverse flow.

4. Studies on the surface homogenisation of softwoods of extreme variability in density within individual sections of timber

A permanent change in structure or permanent reduction in void volume and hence greater proportion of cell wall to cell lumen, ultimately leads to an increase in surface hardness (Tarkow and Seborg, 1968). This can be achieved by pretreatments before rolling, which reduce the elasticity of the timber and minimize springback (exposure to elevated temperature, to plasticizing solutions of chemicals or combinations of soaking and vacuum/pressure processes). Recovery of timber after compression from levels substantially higher than the elastic limit has been demonstrated to be mainly dependent on the compressibility of the voids and on the homogenity in density within the respective specimens. Both characteristics have to be considered before the viability of compression rolling to improve the surface quality of some timbers (Pinus spp.) is to be considered either practical or desirable.

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